US009328575B2

(12) **United States Patent**
Feasey et al.

(10) **Patent No.: US 9,328,575 B2**
(45) **Date of Patent: May 3, 2016**

(54) **DUAL GRADIENT MANAGED PRESSURE DRILLING**

(71) Applicant: **Weatherford Technology Holdings, LLC**, Houston, TX (US)

(72) Inventors: **Guy F. Feasey**, Houston, TX (US); **David Pavel**, Kingwood, TX (US); **Mark A. Mitchell**, Pearland, TX (US)

(73) Assignee: **Weatherford Technology Holdings, LLC**, Houston, TX (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 515 days.

(21) Appl. No.: **13/752,804**

(22) Filed: **Jan. 29, 2013**

(65) **Prior Publication Data**

US 2013/0192841 A1 Aug. 1, 2013

Related U.S. Application Data

(60) Provisional application No. 61/593,018, filed on Jan. 31, 2012.

(51) **Int. Cl.**
E21B 7/12 (2006.01)
E21B 21/08 (2006.01)
E21B 21/00 (2006.01)

(52) **U.S. Cl.**
CPC . ***E21B 21/08*** (2013.01); ***E21B 7/12*** (2013.01); ***E21B 21/001*** (2013.01)

(58) **Field of Classification Search**
CPC E21B 7/12; E21B 7/128; E21B 21/001; E21B 21/08
USPC 166/336, 358; 175/5, 7, 40, 48, 207
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,603,409 A * 9/1971 Watkins 175/7
3,721,292 A 3/1973 Ahlstone
4,059,148 A 11/1977 Blomsma

(Continued)

FOREIGN PATENT DOCUMENTS

WO 00/75477 A1 12/2000
WO 01/94740 A1 12/2001

(Continued)

OTHER PUBLICATIONS

Atkinson, Ian, et al.—A New Horizon in Multiphase Flow Measurement, Oilfield Review. Winter 2004/2005, pp. 52-63.

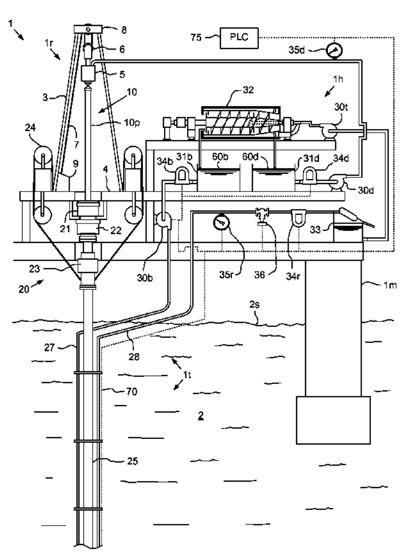
(Continued)

Primary Examiner — Matthew R Buck
(74) *Attorney, Agent, or Firm* — Patterson & Sheridan, LLP

(57) **ABSTRACT**

A method of drilling a subsea wellbore includes drilling the wellbore by injecting drilling fluid through a tubular string extending into the wellbore from an offshore drilling unit (ODU) and rotating a drill bit disposed on a bottom of the tubular string. The method further includes, while drilling the wellbore: mixing lifting fluid with drilling returns at a flow rate proportionate to a flow rate of the drilling fluid, thereby forming a return mixture. The lifting fluid has a density substantially less than a density of the drilling fluid. The return mixture has a density substantially less than the drilling fluid density. The method further includes, while drilling the wellbore: measuring a flow rate of the returns or the return mixture; and comparing the measured flow rate to the drilling fluid flow rate to ensure control of a formation being drilled.

26 Claims, 15 Drawing Sheets



(56) **References Cited**

U.S. PATENT DOCUMENTS

4,437,688	A	3/1984	Kramer et al.	
5,168,932	A *	12/1992	Worrall et al.	166/336
6,230,824	B1	5/2001	Peterman et al.	
6,273,193	B1	8/2001	Hermann et al.	
6,530,437	B2 *	3/2003	Maurer et al.	175/5
6,536,540	B2	3/2003	de Boer	
6,668,943	B1 *	12/2003	Maus et al.	175/5
6,745,857	B2 *	6/2004	Gjedebo	175/69
6,802,379	B2 *	10/2004	Dawson et al.	175/38
6,843,331	B2	1/2005	de Boer	
6,913,092	B2	7/2005	Bourgoyne et al.	
6,926,101	B2	8/2005	deBoer	
6,966,392	B2	11/2005	deBoer	
7,090,036	B2	8/2006	deBoer	
7,093,662	B2	8/2006	deBoer	
7,350,597	B2 *	4/2008	Reitsma et al.	175/66
7,367,411	B2 *	5/2008	Leuchtenberg	175/48
7,584,801	B2	9/2009	deBoer	
7,992,654	B2	8/2011	deBoer	
8,033,335	B2 *	10/2011	Orbell et al.	166/367
8,066,079	B2	11/2011	de Boer	
8,176,985	B2 *	5/2012	Humphreys	166/358
8,322,460	B2 *	12/2012	Horton et al.	175/5
8,403,059	B2 *	3/2013	Hughes et al.	166/367
8,490,719	B2 *	7/2013	Duhe et al.	175/57
8,757,272	B2 *	6/2014	Couturier et al.	166/373
2004/0065440	A1 *	4/2004	Farabee et al.	166/358
2004/0084213	A1 *	5/2004	DeBoer	175/5
2006/0157282	A1	7/2006	Tilton et al.	
2011/0108282	A1 *	5/2011	Kozicz et al.	166/367
2011/0168410	A1	7/2011	deBoer	
2012/0037361	A1 *	2/2012	Santos	E21B 21/08 166/250.08
2012/0234550	A1 *	9/2012	Dietz	E21B 21/08 166/344

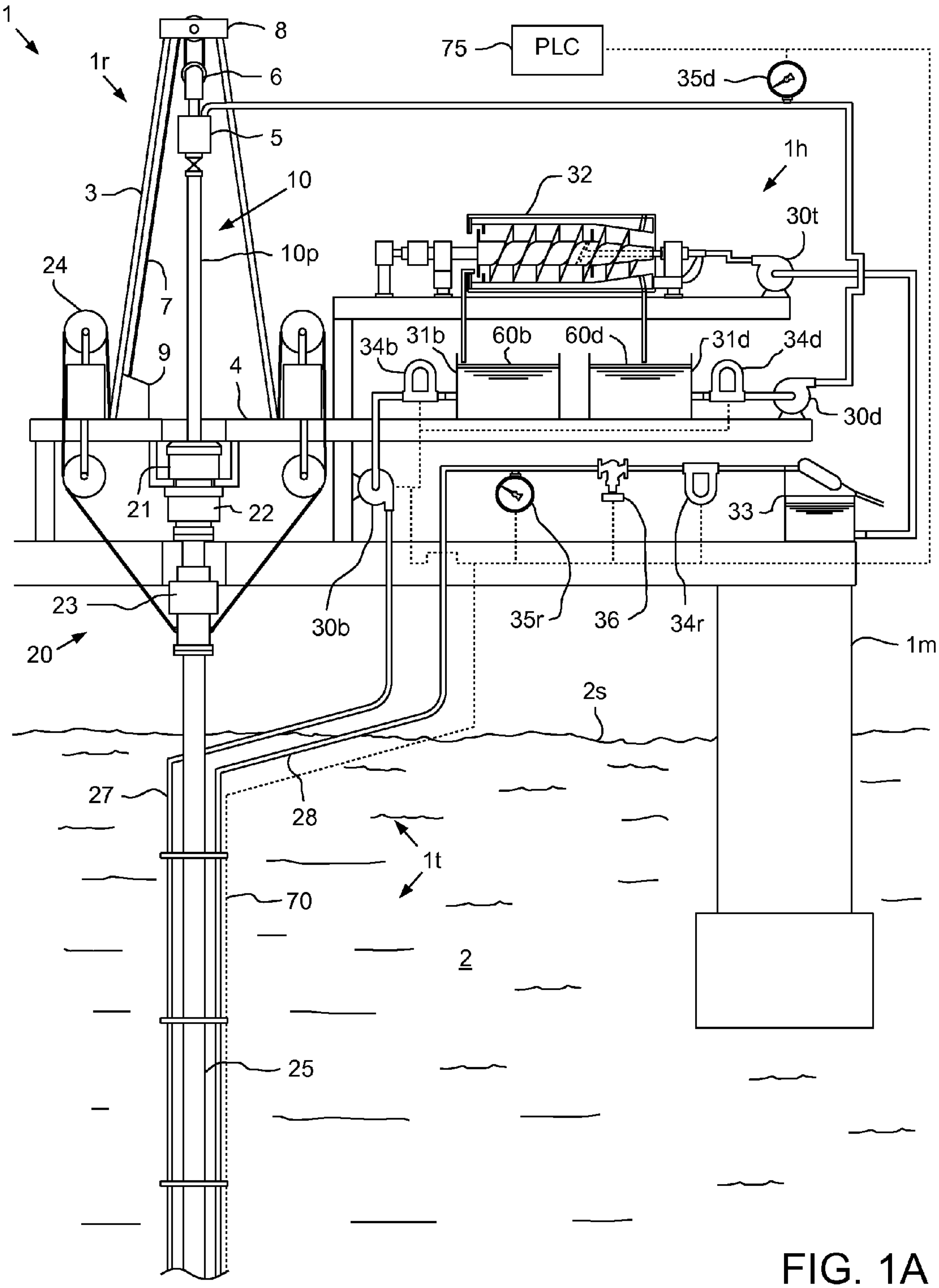
FOREIGN PATENT DOCUMENTS

WO	02/50398	A1	6/2002
WO	2004/033845	A2	4/2004
WO	2011058031	A2	5/2011
WO	2012035001	A2	3/2012

OTHER PUBLICATIONS

PCT International Search Report and Written Opinion, dated Mar. 20, 2014, for International Application No. PCT/US2013/023916.

* cited by examiner



1
1r
8
6
5
75
PLC
35d
1h
32
10
3
10p
30t
24
7
9
4
34b
31b
60b
60d
31d
34d
30d
21
22
33
23
30b
35r
36
34r
20
1m
2s
27
28
1t
70
2
25

FIG. 1A

FIG. 1B

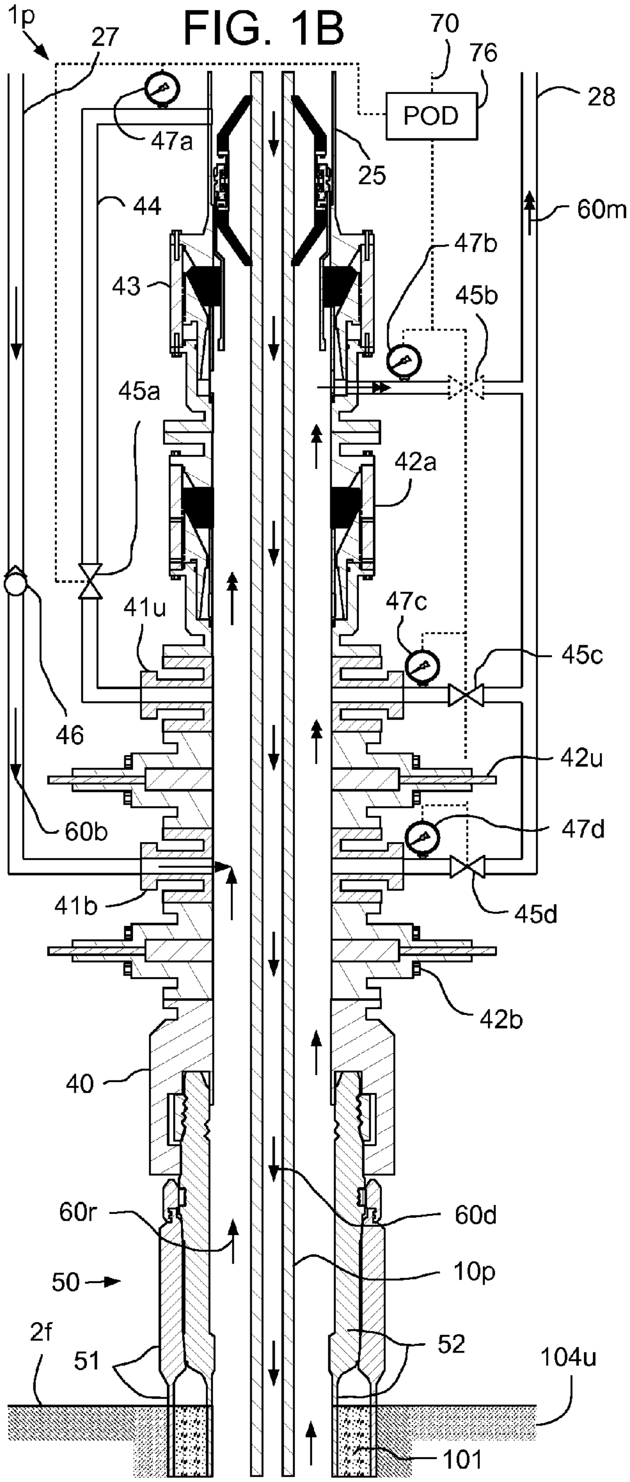

1p
27
70
76
POD
28
47a
25
44
60m
47b
43
45b
45a
42a
47c
41u
45c
46
42u
60b
47d
41b
45d
42b
40
60r
60d
50
10p
2f
51
52
104u
101

FIG. 1C

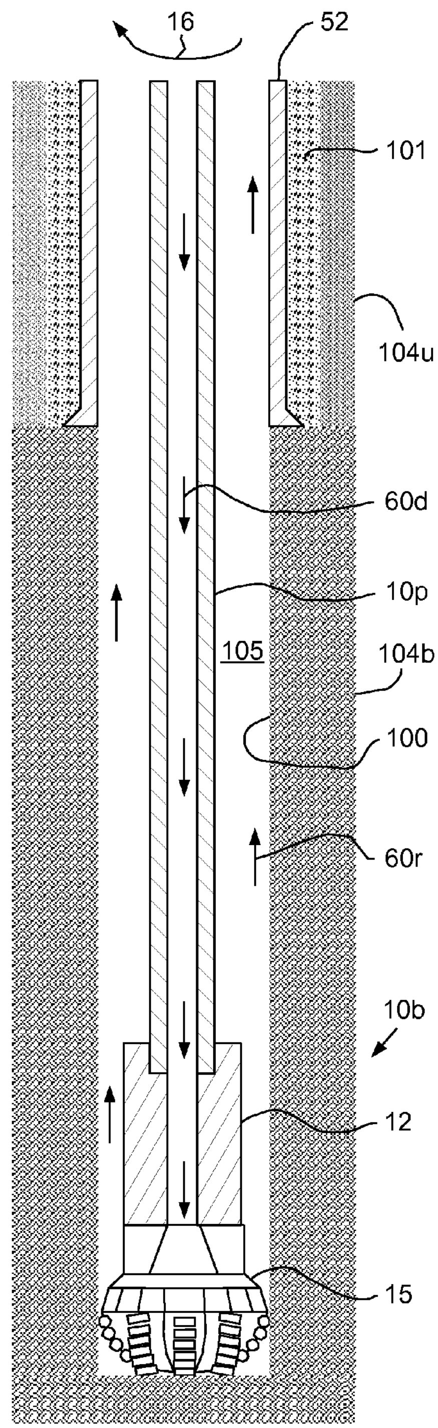
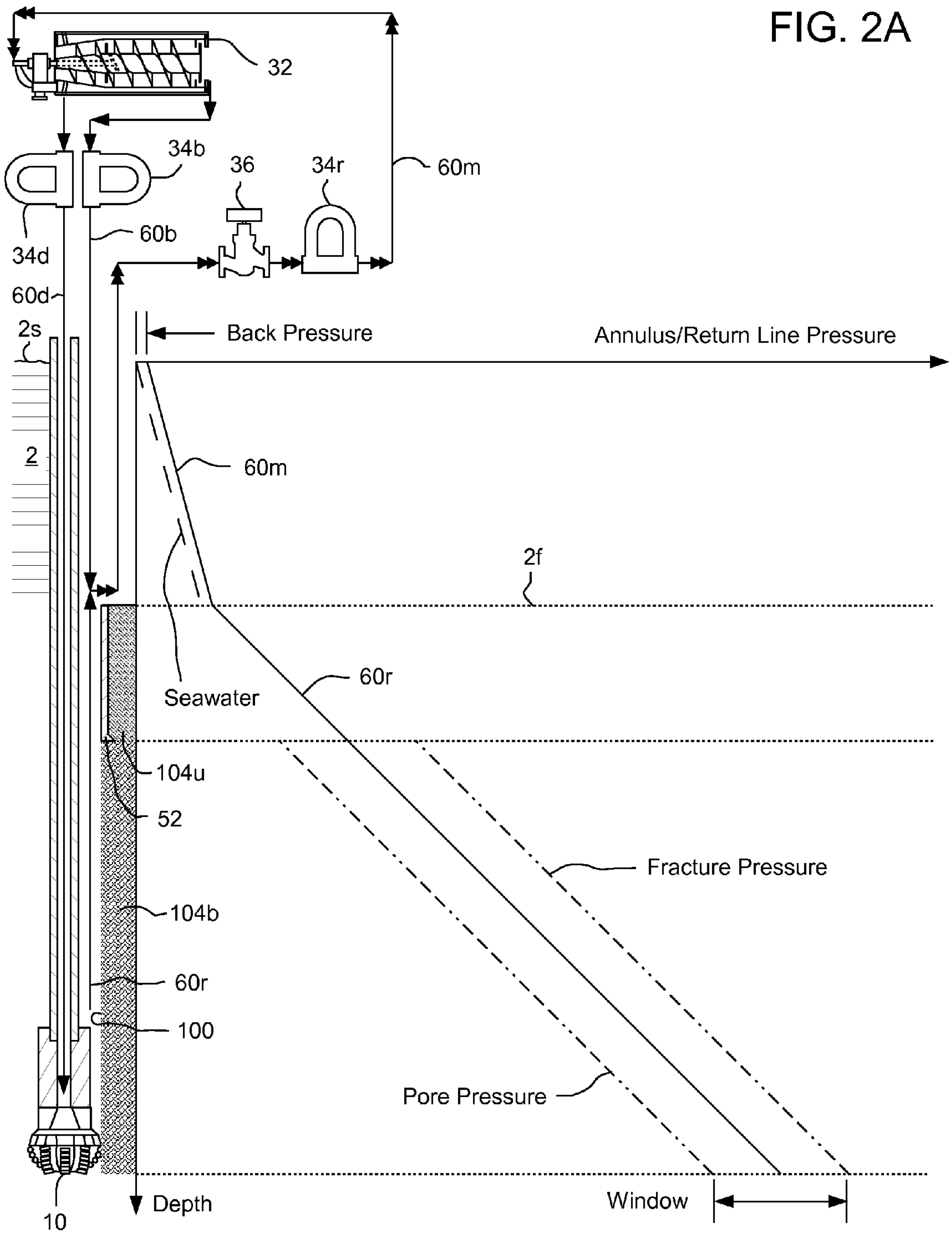
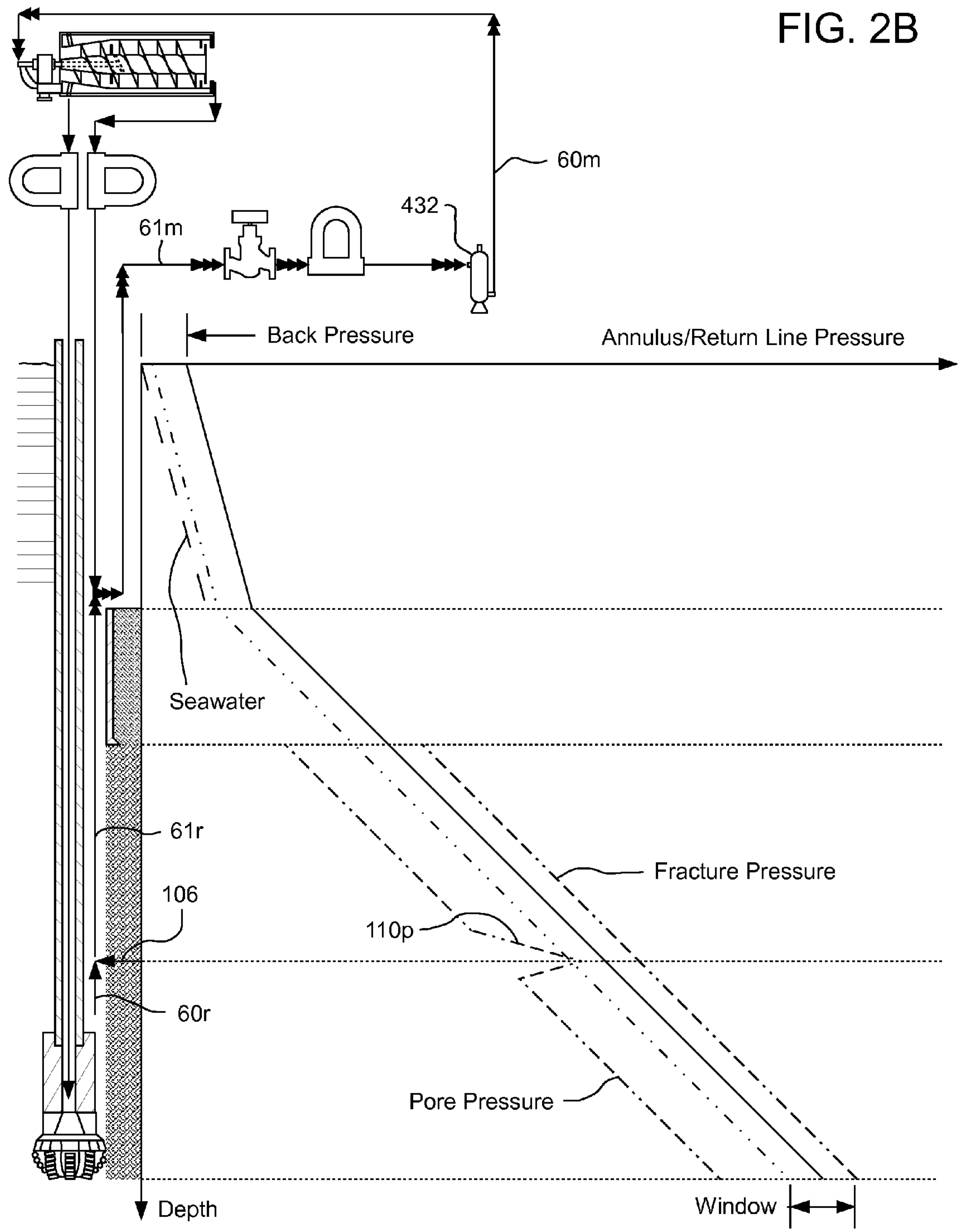

16
52
101
104u
60d
10p
105
104b
100
60r
10b
12
15

FIG. 2A



32
34b
36
34r
60m
34d
60b
60d
2s
Back Pressure
Annulus/Return Line Pressure
2
60m
2f
Seawater
60r
104u
52
Fracture Pressure
104b
60r
100
Pore Pressure
10
Depth
Window

FIG. 2B



60m
432
61m
Back Pressure
Annulus/Return Line Pressure
Seawater
61r
106
110p
Fracture Pressure
60r
Pore Pressure
Depth
Window

FIG. 2C

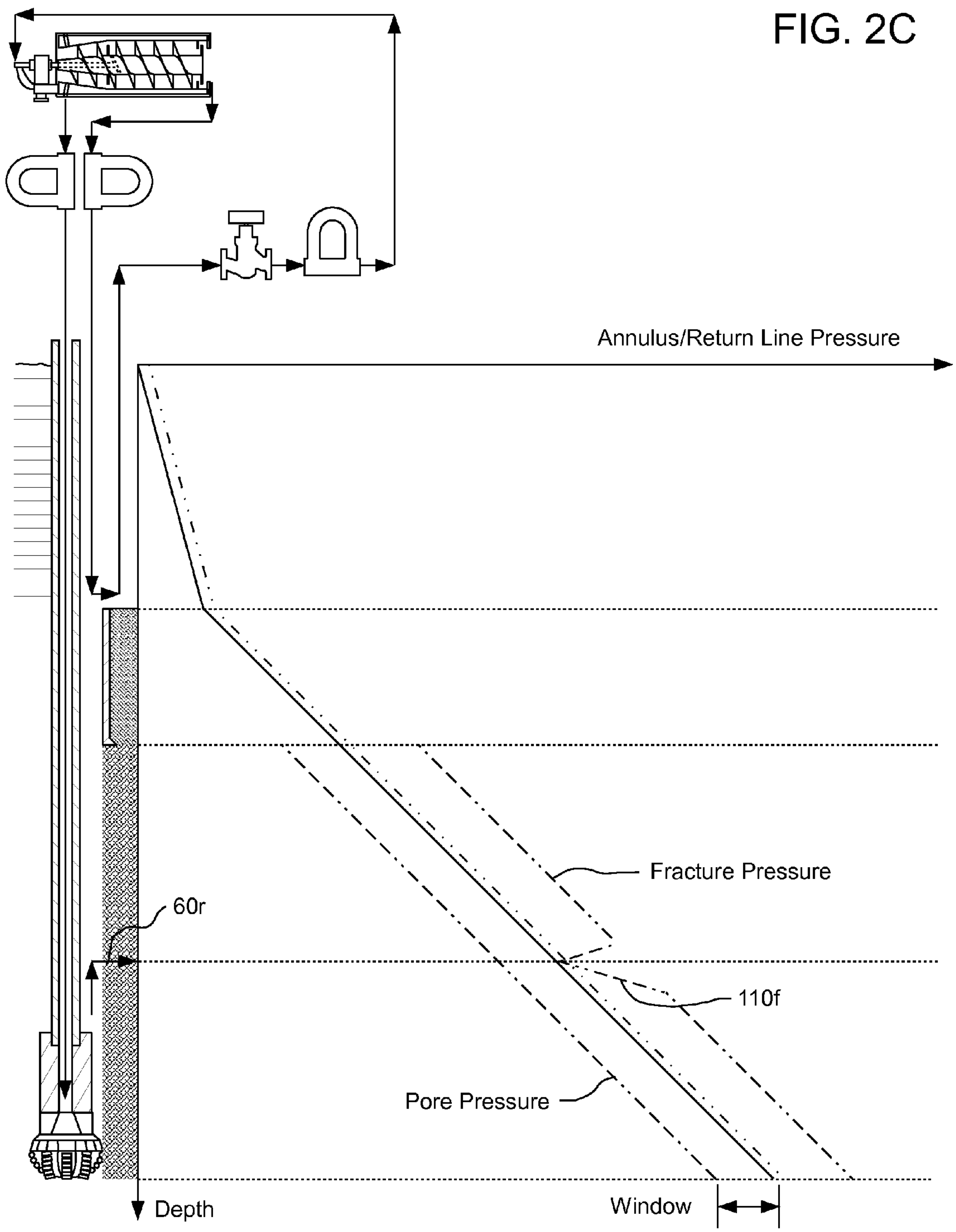

Annulus/Return Line Pressure
Fracture Pressure
60r
110f
Pore Pressure
Depth
Window

FIG. 2D

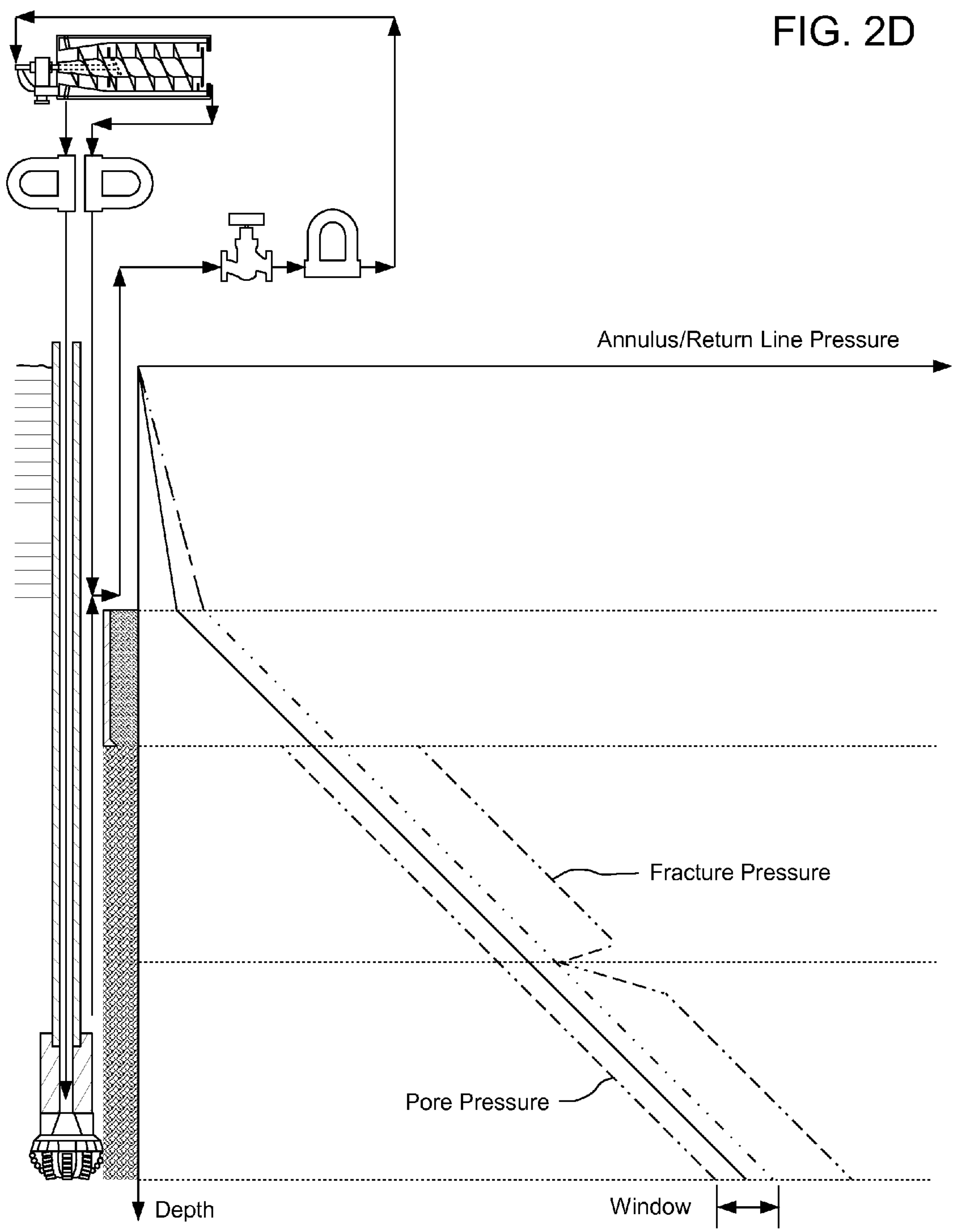

Annulus/Return Line Pressure
Fracture Pressure
Pore Pressure
Depth
Window

FIG. 3A

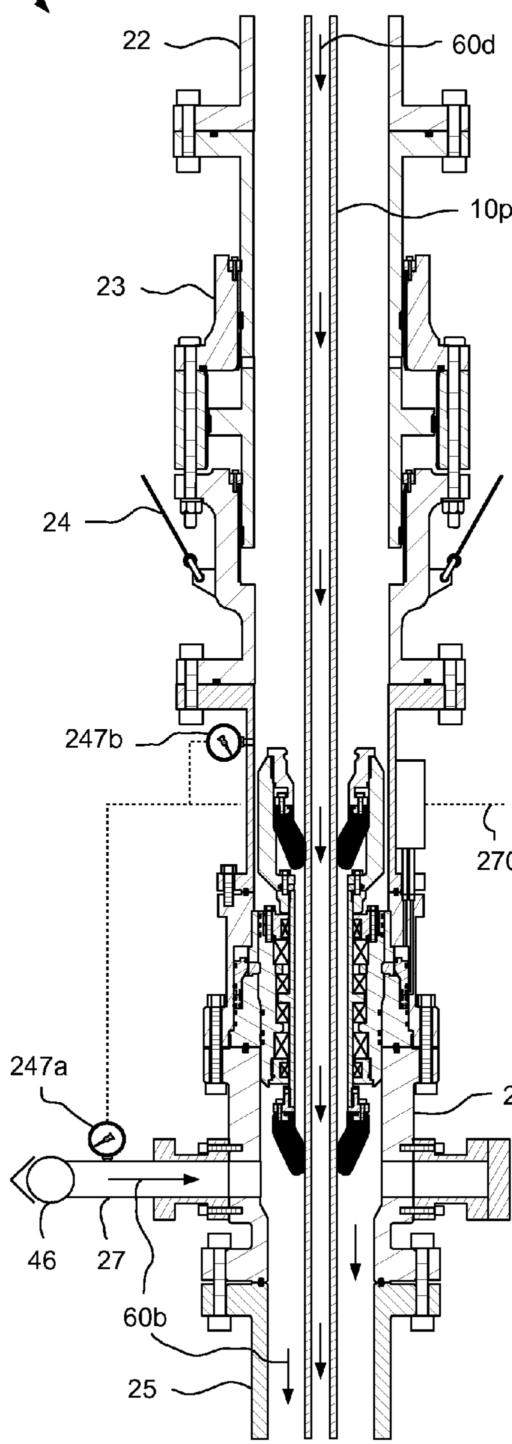
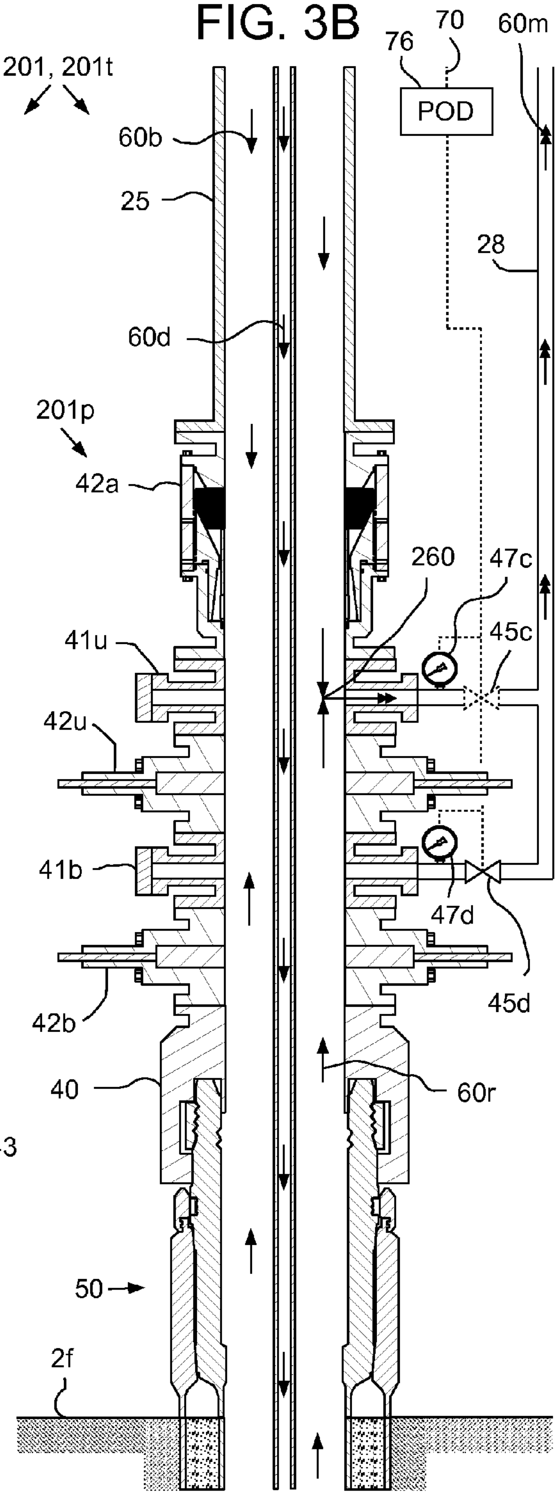
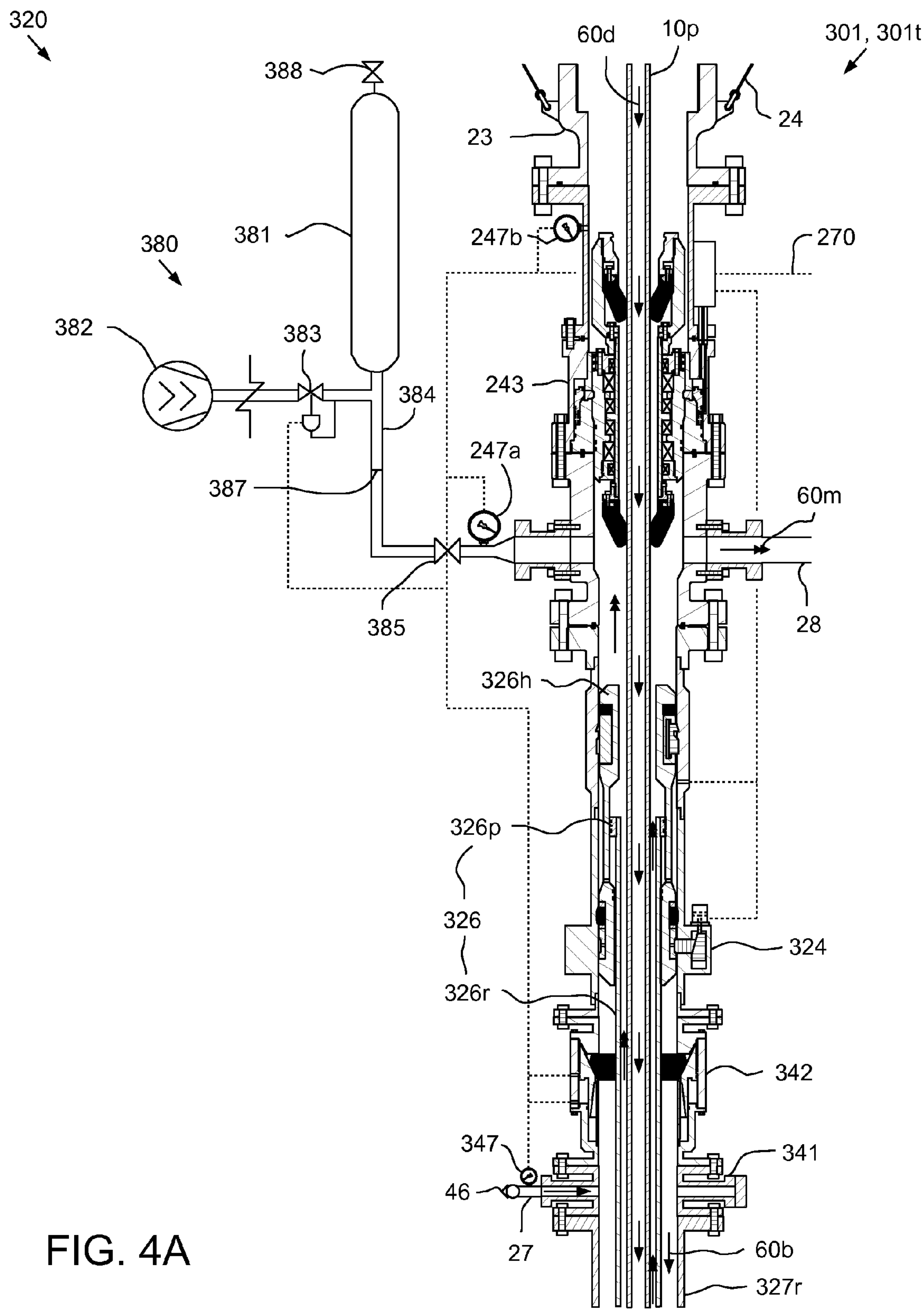

220
22
60d
10p
23
24
247b
270
247a
243
46
27
60b
25

FIG. 3B


201, 201t
76
70
60m
POD
60b
25
28
60d
201p
42a
260
47c
45c
41u
42u
41b
47d
45d
42b
40
60r
50
2f



320
60d
10p
301, 301t
388
23
24
381
247b
270
380
382
383
243
384
247a
60m
387
385
28
326h
326p
326
324
326r
342
347
341
46
27
60b
327r

FIG. 4A

FIG. 4B

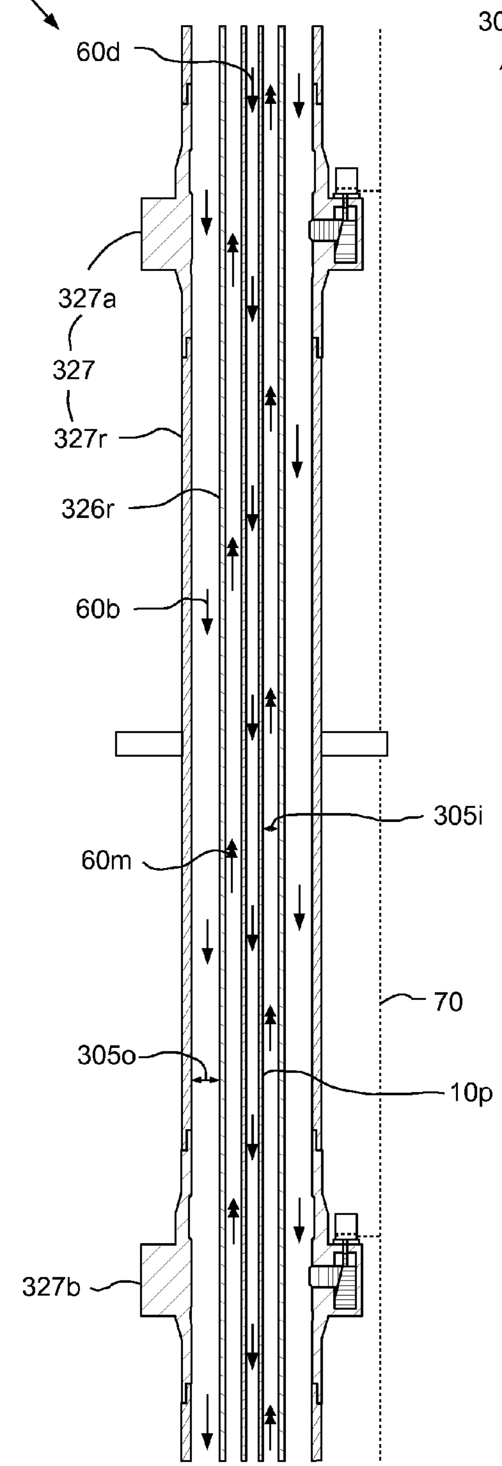
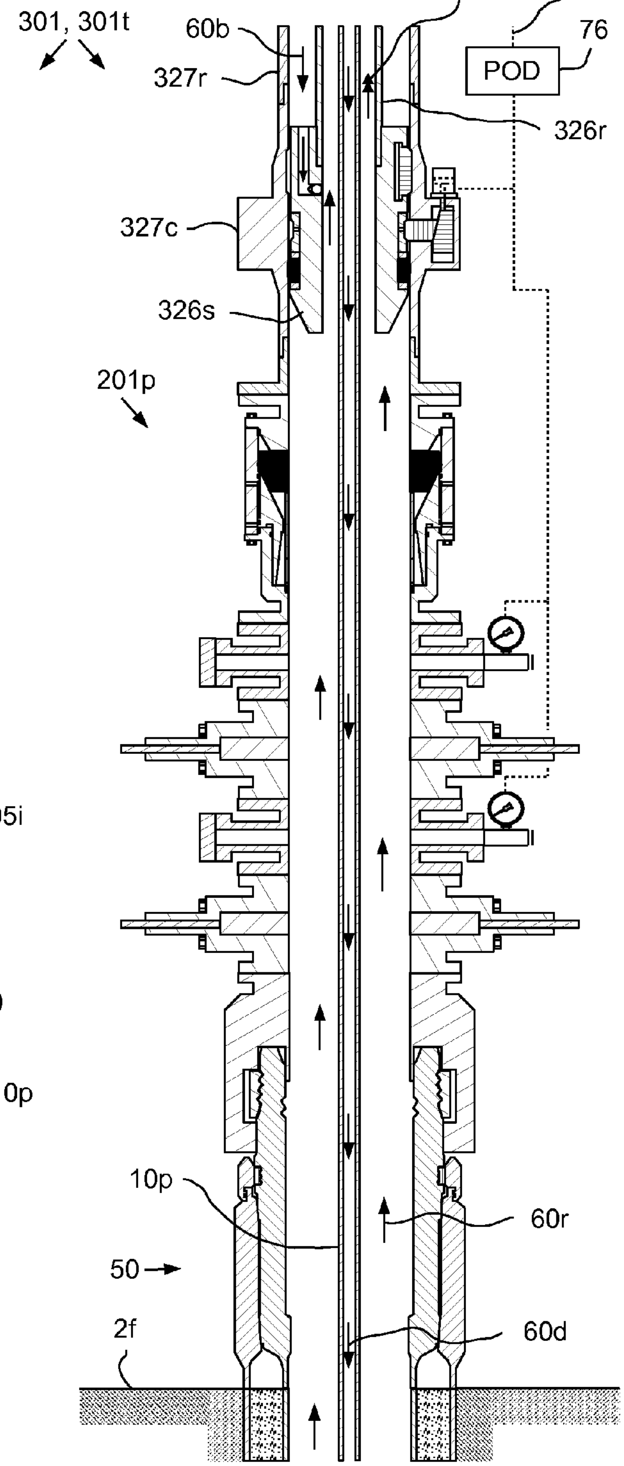
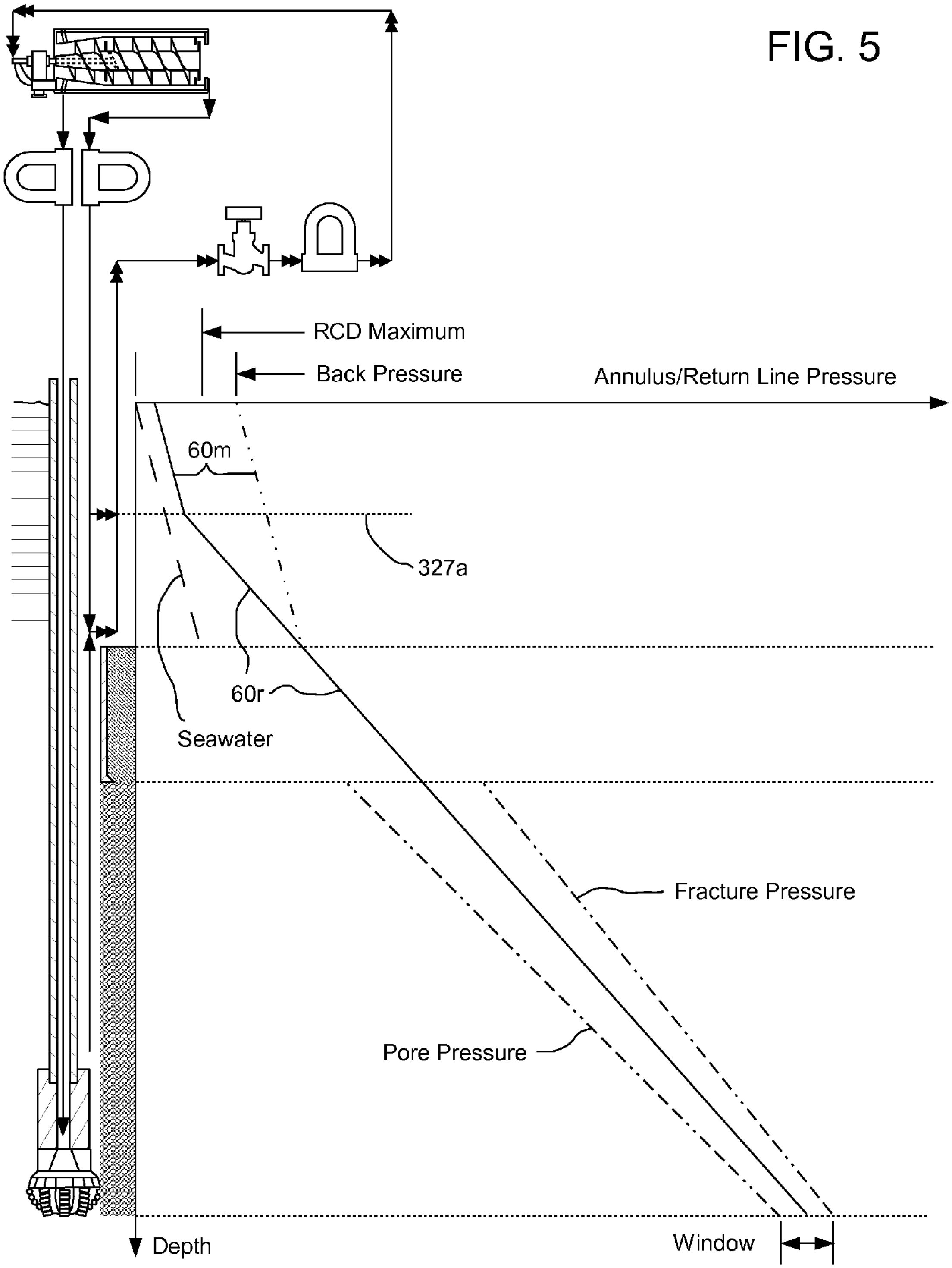

325
60d
327a
327
327r
326r
60b
60m
305o
327b
305i
70
10p

FIG. 4C


301, 301t
60b
327r
60m
70
76
POD
326r
327c
326s
201p
10p
60r
50
2f
60d



RCD Maximum
Back Pressure
Annulus/Return Line Pressure
60m
327a
60r
Seawater
Fracture Pressure
Pore Pressure
Depth
Window

FIG. 5

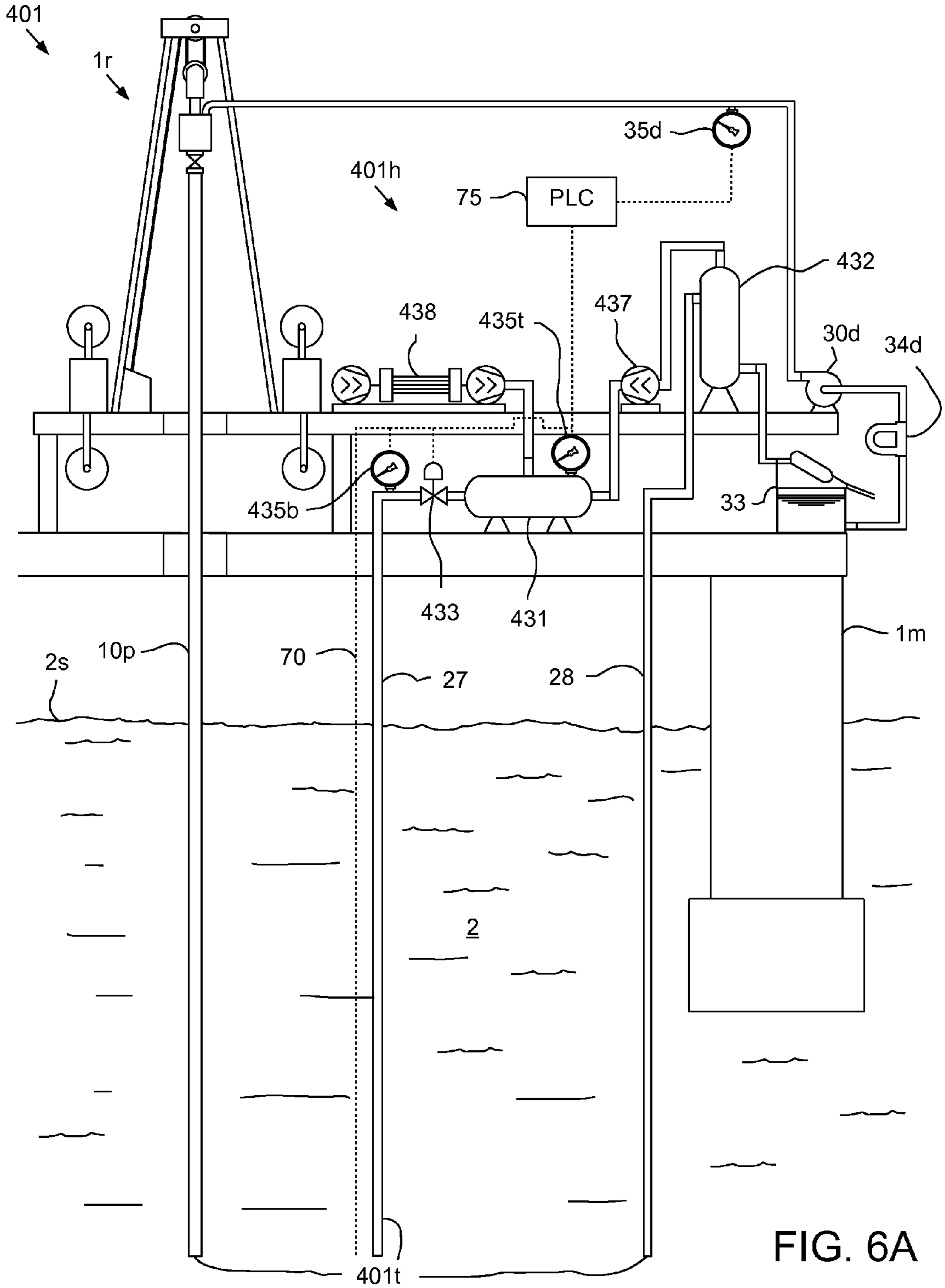

401
1r
401h
75
PLC
35d
432
438
435t
437
30d
34d
435b
33
433
431
1m
2s
10p
70
27
28
2
401t

FIG. 6A

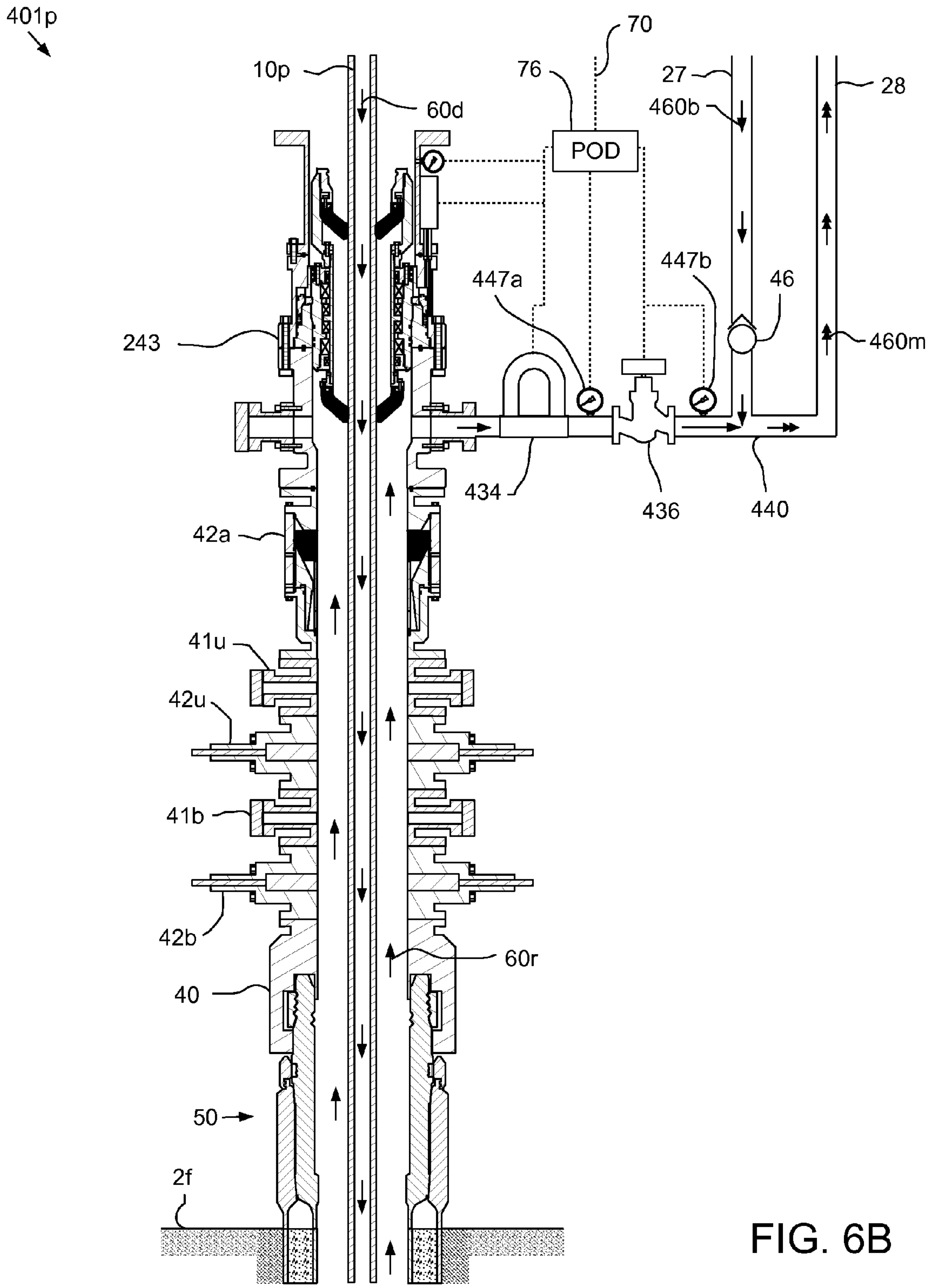

401p
70
10p
76
27
28
60d
460b
POD
447b
447a
46
243
460m
434
436
440
42a
41u
42u
41b
42b
60r
40
50
2f

FIG. 6B

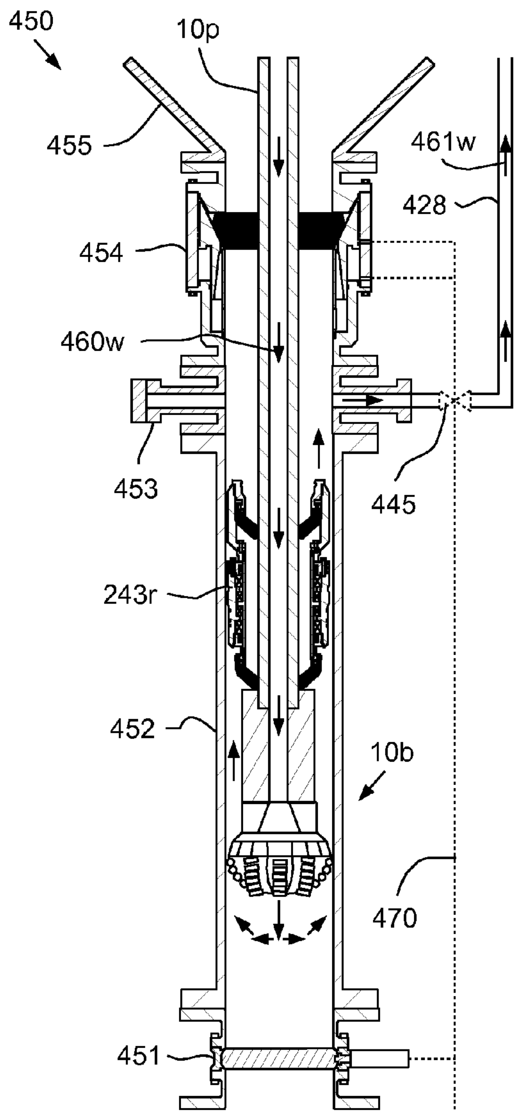

450
10p
455
461w
428
454
460w
453
445
243r
452
10b
470
451

FIG. 6C

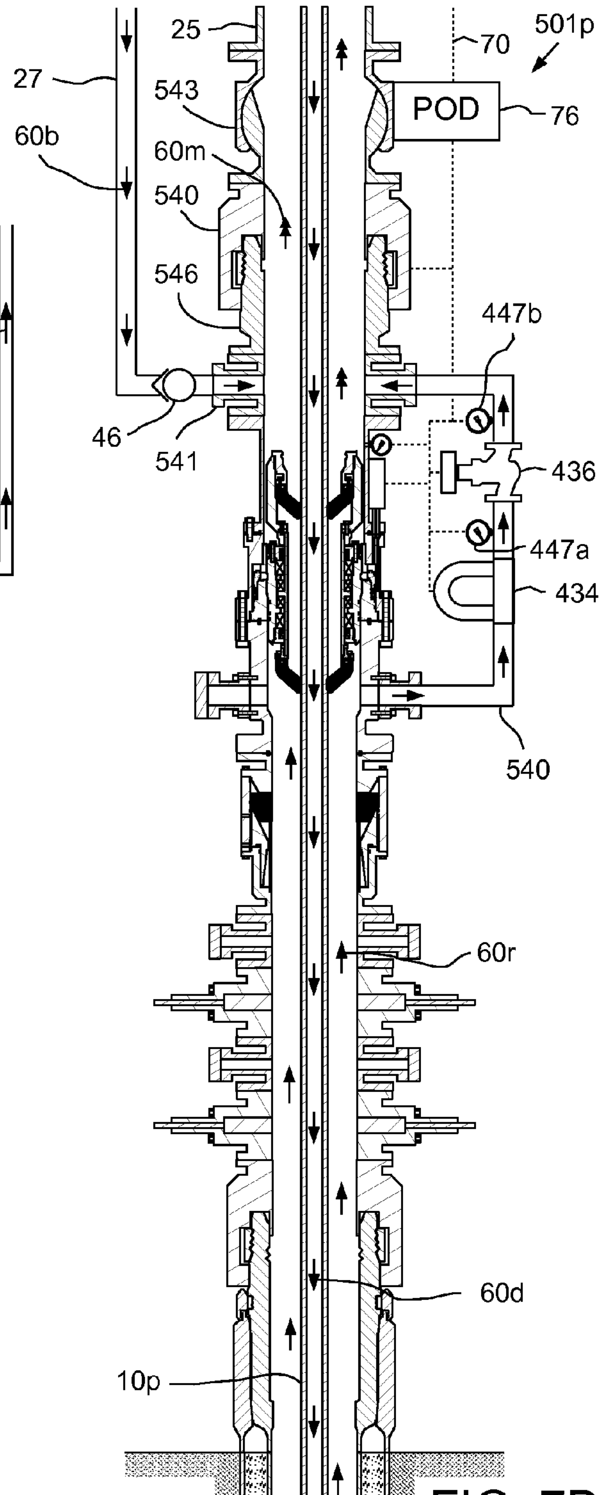

25
70
501p
27
543
POD
76
60b
60m
540
546
447b
46
541
436
447a
434
540
60r
60d
10p

FIG. 7B

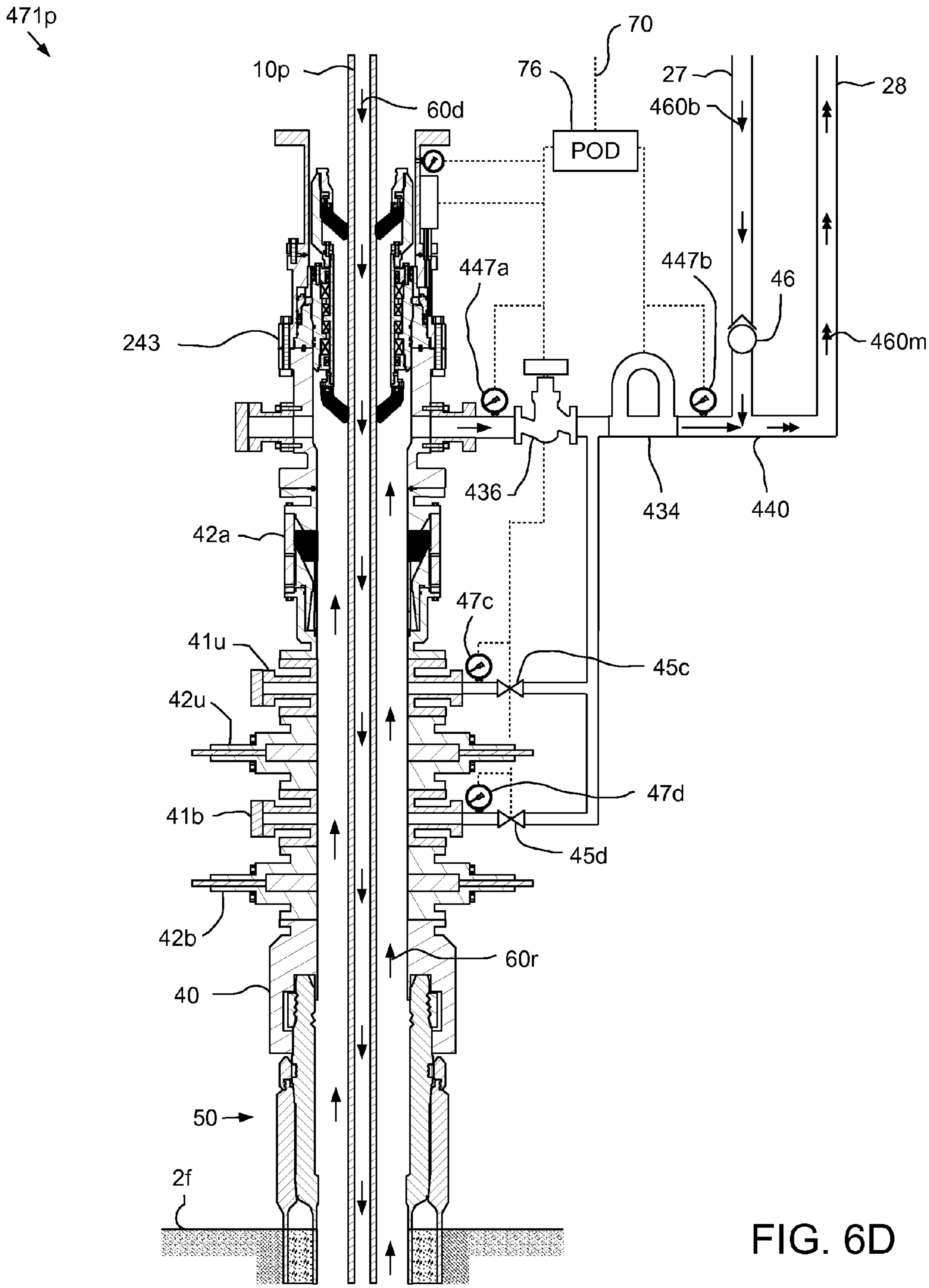

471p
10p
60d
76
70
POD
27
460b
28
447a
447b
46
460m
243
436
434
440
42a
47c
41u
45c
42u
47d
41b
45d
42b
60r
40
50
2f

FIG. 6D

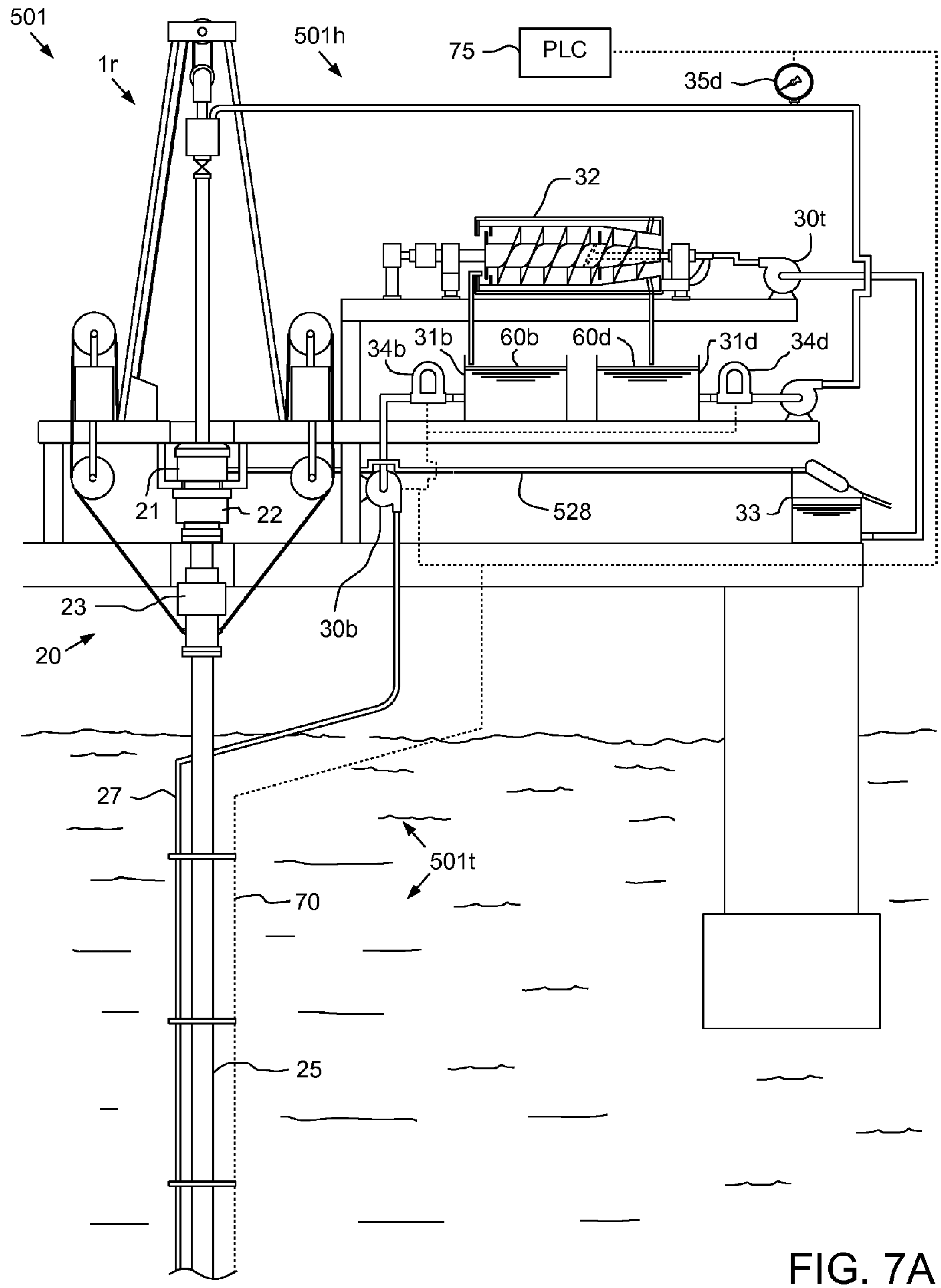

501
1r
501h
75
PLC
35d
32
30t
34b
31b
60b
60d
31d
34d
21
22
528
33
23
20
30b
27
501t
70
25

FIG. 7A

DUAL GRADIENT MANAGED PRESSURE DRILLING

BACKGROUND OF THE INVENTION

1. Field of the Invention

Embodiments of the present invention generally relate to dual gradient managed pressure drilling.

2. Description of the Related Art

In well construction and completion operations, a wellbore is formed to access hydrocarbon-bearing formations (e.g., crude oil and/or natural gas) by the use of drilling. Drilling is accomplished by utilizing a drill bit that is mounted on the end of a drill string. To drill within the wellbore to a predetermined depth, the drill string is often rotated by a top drive or rotary table on a surface platform or rig, and/or by a downhole motor mounted towards the lower end of the drill string. After drilling to a predetermined depth, the drill string and drill bit are removed and a section of casing is lowered into the wellbore. An annulus is thus formed between the string of casing and the formation. The casing string is temporarily hung from the surface of the well. A cementing operation is then conducted in order to fill the annulus with cement. The casing string is cemented into the wellbore by circulating cement into the annulus defined between the outer wall of the casing and the borehole. The combination of cement and casing strengthens the wellbore and facilitates the isolation of certain areas of the formation behind the casing for the production of hydrocarbons.

Deep water off-shore drilling operations are typically carried out by a mobile offshore drilling unit (MODU), such as a drill ship or a semi-submersible, having the drilling rig aboard and often make use of a marine riser extending between the wellhead of the well that is being drilled in a subsea formation and the MODU. The marine riser is a tubular string made up of a plurality of tubular sections that are connected in end-to-end relationship. The riser allows return of the drilling mud with drill cuttings from the hole that is being drilled. Also, the marine riser is adapted for being used as a guide for lowering equipment (such as a drill string carrying a drill bit) into the hole.

SUMMARY OF THE INVENTION

Embodiments of the present invention generally relate to dual gradient managed pressure drilling. In one embodiment, a method of drilling a subsea wellbore includes drilling the wellbore by injecting drilling fluid through a tubular string extending into the wellbore from an offshore drilling unit (ODU) and rotating a drill bit disposed on a bottom of the tubular string. The drilling fluid exits the drill bit and carries cuttings from the drill bit. The drilling fluid and cuttings (returns) flow to a floor of the sea via an annulus defined by an outer surface of the tubular string and an inner surface of the wellbore. The method further includes, while drilling the wellbore: mixing lifting fluid with the returns at a flow rate proportionate to a flow rate of the drilling fluid, thereby forming a return mixture. The lifting fluid has a density substantially less than a density of the drilling fluid. The return mixture has a density substantially less than the drilling fluid density. The method further includes, while drilling the wellbore: measuring a flow rate of the returns or the return mixture; and comparing the measured flow rate to the drilling fluid flow rate to ensure control of a formation being drilled.

In another embodiment, a method of drilling a subsea wellbore includes: drilling the wellbore by injecting drilling fluid through a tubular string extending into the wellbore from

an offshore drilling unit (ODU) and rotating a drill bit disposed on a bottom of the tubular string. The drilling fluid exits the drill bit and carries cuttings from the drill bit. The drilling fluid and cuttings (returns) flow to a floor of the sea via an annulus defined by an outer surface of the tubular string and an inner surface of the wellbore. The returns flow from the seafloor to a subsea pressure control assembly (PCA) via a subsea wellhead. The subsea PCA comprises a mass flow meter. The method further includes, while drilling the wellbore: measuring a flow rate of the returns using the mass flow meter; and comparing the measured flow rate to the drilling fluid flow rate to ensure control of a formation being drilled.

BRIEF DESCRIPTION OF THE DRAWINGS

So that the manner in which the above recited features of the present invention can be understood in detail, a more particular description of the invention, briefly summarized above, may be had by reference to embodiments, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only typical embodiments of this invention and are therefore not to be considered limiting of its scope, for the invention may admit to other equally effective embodiments.

FIGS. **1**A-**1**C illustrate an offshore drilling system, according to one embodiment of the present invention.

FIG. **2**A illustrates operation of a programmable logic controller (PLC) of the drilling system during drilling of an ideal lower formation. FIG. **2**B illustrates operation of the PLC during drilling of a lower formation having an abnormally high pressure region. FIGS. **2**C and **2**D illustrate operation of the PLC during drilling of a lower formation having an abnormally low pressure region.

FIG. **3**A illustrates a portion of an upper marine riser package (UMRP) of an offshore drilling system, according to another embodiment of the present invention. FIG. **3**B illustrates a pressure control assembly (PCA) of the drilling system.

FIG. **4**A illustrates a portion of an UMRP of an offshore drilling system, according to another embodiment of the present invention. FIG. **4**B illustrates a portion of a concentric marine riser of the drilling system. FIG. **4**C illustrates connection of the concentric riser to the PCA.

FIG. **5** illustrates selection of a location of an inner riser shoe of the concentric riser.

FIGS. **6**A and **6**B illustrate an offshore drilling system, according to another embodiment of the present invention. FIG. **6**C illustrates a lubricator for use with the drilling system. FIG. **6**D illustrates an alternative PCA for use with the drilling system.

FIGS. **7**A and **7**B illustrate an offshore drilling system, according to another embodiment of the present invention.

DETAILED DESCRIPTION

FIGS. **1**A-**1**C illustrate an offshore drilling system **1**, according to one embodiment of the present invention. The drilling system **1** may include a MODU **1***m*, such as a semi-submersible, a drilling rig **1***r*, a fluid handling system **1***h*, a fluid transport system **1***t*, and a pressure control assembly (PCA) **1***p*. The MODU **1***m* may carry the drilling rig **1***r* and the fluid handling system **1***h* aboard and may include a moon pool, through which drilling operations are conducted. The semi-submersible may include a lower barge hull which floats below a surface (aka waterline) **2***s* of sea **2** and is, therefore, less subject to surface wave action. Stability columns (only one shown) may be mounted on the lower barge hull for supporting an upper hull above the waterline. The upper hull may have one or more decks for carrying the drilling rig **1r** and fluid handling system **1h**. The MODU **1m** may further have a dynamic positioning system (DPS) (not shown) and/or be moored for maintaining the moon pool in position over a subsea wellhead **50**.

Alternatively, the MODU **1m** may be a drill ship. Alternatively, a fixed offshore drilling unit or a non-mobile floating offshore drilling unit may be used instead of the MODU **1m**. Alternatively, the wellhead may be located adjacent to the waterline **2s** and the drilling rig **1r** may be a located on a platform adjacent to the wellhead. Alternatively, a Kelly and rotary table (not shown) may be used instead of the top drive. Alternatively, the drilling system may be used for drilling a subterranean (aka land based) wellbore and the MODU may be omitted.

The drilling rig **1r** may include a derrick **3** having a rig floor **4** at its lower end having an opening corresponding to the moonpool. The drilling rig **1r** may further include a top drive **5**. The top drive **5** may include a motor for rotating **16** a drill string **10**. The top drive motor may be electric or hydraulic. A housing of the top drive **5** may be coupled to a rail (not shown) of the rig **1r** for preventing rotation of the top drive housing during rotation of the drill string **10** and allowing for vertical movement of the top drive with a traveling block **6**. A housing of the top drive **5** may be suspended from the derrick **3** by the traveling block **6**. The traveling block **6** may be supported by wire rope **7** connected at its upper end to a crown block **8**. The wire rope **7** may be woven through sheaves of the blocks **6**, **8** and extend to drawworks **9** for reeling thereof, thereby raising or lowering the traveling block **6** relative to the derrick **3**. A Kelly valve may be connected to a quill of a top drive **5**. A top of the drill string **10** may be connected to the Kelly valve, such as by a threaded connection or by a gripper (not shown), such as a torque head or spear. The drilling rig **1r** may further include a drill string compensator (not shown) to account for heave of the MODU **1m**. The drill string compensator may be disposed between the traveling block **6** and the top drive **5** (aka hook mounted) or between the crown block **8** and the derrick **3** (aka top mounted).

The fluid transport system **1t** may include the drill string **10**, an upper marine riser package (UMRP) **20**, a marine riser **25**, and one or more auxiliary lines, such as a lift line **27** and a return line **28**. The drill string **10** may include a bottomhole assembly (BHA) **10b** and joints of drill pipe **10p** connected together, such as by threaded couplings. The BHA **10b** may be connected to the drill pipe **10p**, such as by a threaded connection, and include a drill bit **15** and one or more drill collars **12** connected thereto, such as by a threaded connection. The drill bit **15** may be rotated **16** by the top drive **5** via the drill pipe **10p** and/or the BHA **10b** may further include a drilling motor (not shown) for rotating the drill bit. The BHA **10b** may further include an instrumentation sub (not shown), such as a measurement while drilling (MWD) and/or a logging while drilling (LWD) sub.

The PCA **1p** may be connected to a wellhead **50** located adjacent to a floor **2f** of the sea **2**. A conductor string **51** may be driven into the seafloor **2f**. The conductor string **51** may include a housing and joints of conductor pipe connected together, such as by threaded connections. Once the conductor string **51** has been set, a subsea wellbore **100** may be drilled into the seafloor **2f** and a casing string **52** may be deployed into the wellbore. The casing string **52** may include a wellhead housing and joints of casing connected together, such as by threaded connections. The wellhead housing may land in the conductor housing during deployment of a casing string **52**. The casing string **52** may be cemented **101** into the wellbore **100**. The casing string **52** may extend to a depth adjacent a bottom of an upper formation **104u**. The upper formation **104u** may be non-productive and a lower formation **104b** may be a hydrocarbon-bearing reservoir. Alternatively, the lower formation **104b** may be environmentally sensitive, such as an aquifer, or unstable. Although shown as vertical, the wellbore **100** may include a vertical portion and a deviated, such as horizontal, portion.

The PCA **1p** may include a wellhead adapter **40**, one or more flow crosses **41u,b**, one or more blow out preventers (BOPs) **42a,u,b**, a subsea rotating control device (RCD) **43**, a lower marine riser package (LMRP) (only control pod **76** shown), one or more accumulators (not shown), and a receiver (see receiver **546** of PCA **501p** in FIG. **7B**). The LMRP may include the control pod **76**, a flex joint (see flex joint **543** of PCA **501p** in FIG. **7B**), and a connector (see connector **540** of PCA **501p** in FIG. **7B**). The wellhead adapter **40**, flow crosses **41u,b**, BOPs **42a,u,b**, RCD **43**, receiver, connector, and flex joint may each include a housing having a longitudinal bore therethrough and may each be connected, such as by flanges, such that a continuous bore is maintained therethrough. The bore may have drift diameter, corresponding to a drift diameter of the wellhead **50**.

Each of the connector and wellhead adapter **40** may include one or more fasteners, such as dogs, for fastening the LMRP to the BOPS **42a,u,b** and the PCA **1p** to an external profile of the wellhead housing, respectively. Each of the connector and wellhead adapter **40** may further include a seal sleeve for engaging an internal profile of the respective receiver and wellhead housing. Each of the connector and wellhead adapter **40b** may be in electric or hydraulic communication with the control pod **76** and/or further include an electric or hydraulic actuator and an interface, such as a hot stab, so that a remotely operated subsea vehicle (ROV) (not shown) may operate the actuator for engaging the dogs with the external profile.

The LMRP may receive a lower end of the riser **25** and connect the riser to the PCA **1p**. The control pod **76** may be in electric, hydraulic, and/or optical communication with a programmable logic controller (PLC) **75** onboard the MODU **1m** via an umbilical **70**. The control pod **76** may include one or more control valves (not shown) in communication with the BOPs **42a,u,b** for operation thereof. Each control valve may include an electric or hydraulic actuator in communication with the umbilical **70**. The umbilical **70** may include one or more hydraulic or electric control conduit/cables for each actuator. The accumulators may store pressurized hydraulic fluid for operating the BOPs **42a,u,b**. Additionally, the accumulators may be used for operating one or more of the other components of the PCA **1p**. The umbilical **70** may further include hydraulic, electric, and/or optic control conduit/cables for operating various functions of the PCA **1p**. The PLC **75** may operate the PCA **1p** via the umbilical **70** and the control pod **76**.

A lower end of a kill line **44** may be connected to a branch of the upper flow cross **41u** and an upper end of the kill line may be connected to the riser **25** (shown), LMRP, or PCA above a lower portion of the RCD **43**. Barrier fluid, such as kill mud or seawater, may be maintained in the riser **25** during the drilling operation. A shutoff valve **45a** may be disposed in the kill line **44**. A pressure sensor **47a** may be connected to the kill line **44** between the shutoff valve **45a** and the riser **25**. The lift line **27** may be connected to an outlet of a lift pump **30b** and to a branch of the lower cross **41b**. A check valve **46** may be disposed in the lift line **27**. The check valve **46** may be operable to allow fluid flow from the lift pump **30b** to the lower flow cross **41b** and prevent reverse flow from the lower flow cross **41***b* to the lift pump **30***b*. A lower end of the return line **28** may be connected to an outlet of the RCD **43**. A shutoff valve **45***b* may be disposed in the return line **28**. A pressure sensor **47***b* may be connected to the lift line **28** between the shutoff valve **45***b* and the RCD outlet.

An auxiliary manifold may also connect to the return line **28** and have a branch connected to a branch of each flow cross **41***u,b*. Shutoff valves **45***c,d* may be disposed in respective branches of the auxiliary manifold. Pressure sensors **47***c,d* may be connected to the auxiliary manifold branches between respective shutoff valves **45***c,d* and respective flow cross branches. Each pressure sensor **47***a-d* may be in data communication with the control pod **70**. The lines **27**, **28** and umbilical **70** may extend between the MODU **1***m* and the PCA **1***p* and may be fastened along the riser **25** and/or extend separately therefrom. Each line **27**, **28**, **44** may be a flow conduit. Each shutoff valve **45***a-d* may be automated and have a hydraulic actuator (not shown) operable by the control pod **76** via a respective umbilical conduit or the LMRP accumulators. Alternatively, the valve actuators may be electrical or pneumatic. The shutoff valves **45***a,c,d* may be normally closed and the shutoff valve **45***b* may be normally open (depicted in phantom) during the drilling operation.

The RCD **43** may include a housing, a piston, a packing, and a bearing assembly. The housing may be tubular and have one or more sections connected together, such as by flanged connections. The bearing assembly may include a bearing pack, one or more strippers, and a catch sleeve. The bearing assembly may be selectively longitudinally and torsionally connected to the housing by engagement of the packing with the catch sleeve. The housing may have hydraulic ports (not shown) in fluid communication (not shown) with the control pod **76** for selective operation of the piston by the control pod. The bearing pack may support the strippers from the catch sleeve such that the strippers may rotate relative to the housing (and the sleeve). The bearing pack may include one or more radial bearings, one or more thrust bearings, and a self contained lubricant system. The bearing pack may be disposed between the strippers and be housed in and connected to the catch sleeve, such as by a threaded connection and/or fasteners.

Each stripper may include a gland or retainer and a seal. Each stripper seal may be directional and the upper seal may be oriented to seal against the drill pipe **10***p* in response to higher pressure in the riser **25** than the wellbore **100** and the lower stripper seal may be oriented to seal against the drill pipe in response to higher pressure in the wellbore than the riser. Each stripper seal may have a conical shape for fluid pressure to act against a respective tapered surface thereof, thereby generating sealing pressure against the drill pipe **10***p*. Each stripper seal may have an inner diameter slightly less than a pipe diameter of the drill pipe **10***p* to form an interference fit therebetween. Each stripper seal may be flexible enough to accommodate and seal against threaded couplings of the drill pipe **10***p* having a larger tool joint diameter. The drill pipe **10***p* may be received through a bore of the bearing assembly so that the stripper seals may engage the drill pipe. The stripper seals may provide a desired barrier in the riser **25** either when the drill pipe **10***p* is stationary or rotating.

Alternatively, the RCD **243** (FIG. **3**A) may be used instead of the RCD **43**. Alternatively, an active seal RCD may be used and the bearing assembly may be non-releasably connected to the housing. Alternatively, the RCD **43** may be located in the UMRP **20** and the riser **25** used to conduct a return mixture **60***m* to the RCD. Additionally, for the UMRP RCD, the lift line **27** may be connected to the riser **25** at various points therealong for selective location of mixing (FIG. **5**). Alternatively, the RCD **43** may be assembled as part of the riser **25** at any location therealong. Alternatively, both stripper seals may be oriented to seal against the drill pipe **10***p* in response to higher pressure in the wellbore **100** than the riser **25**.

The riser **25** may extend from the PCA **1***p* to the MODU **1***m* and may be connected to the MODU via the UMRP **20**. The UMRP **20** may include a diverter **21**, a flex joint **22**, a slip (aka telescopic) joint **23**, and a tensioner **24**. The slip joint **23** may include an outer barrel connected to an upper end of the riser **25**, such as by a flanged connection, and an inner barrel connected to the flex joint **22**, such as by a flanged connection. The outer barrel may also be connected to the tensioner **24**, such as by a tensioner ring (not shown). The flex joint **22** may also connect to the diverter **21**, such as by a flanged connection. The diverter **21** may also be connected to the rig floor **4**, such as by a bracket.

The slip joint **23** may be operable to extend and retract in response to heave of the MODU **1***m* relative to the riser **25** while the tensioner **24** may reel wire rope in response to the heave, thereby supporting the riser **25** from the MODU **1***m* while accommodating the heave. The flex joints **23** may accommodate respective horizontal and/or rotational (aka pitch and roll) movement of the MODU **1***m* relative to the riser **25** and the riser relative to the PCA **1***p*. The riser **25** may have one or more buoyancy modules (not shown) disposed therealong to reduce load on the tensioner **24**.

The fluid handling system **1***h* may include one or pumps **30***b,d,t*, one or more fluid tanks **31***b,d*, a fluid separator, such as a centrifuge **32**, a solids separator, such as a shale shaker **33**, one or more flow meters **34***b,d,r*, one or more pressure sensors **35***d,r*, and the variable choke valve **36**. An upper end of the return line **28** may be connected to an inlet of the shaker **33**. The pressure sensor **35***r*, choke **36**, and flow meter **34***r* may be assembled as part of an upper portion of the return line **28**. A transfer line may connect a fluid outlet of the shaker **33** to an inlet of a transfer pump **30***t*.

Each pressure sensor **35***d,r* may be in data communication with the PLC **75**. The pressure sensor **35***r* may be connected to the return line **28** between the choke **36** and the shutoff valve **45***b* and may be operable to monitor backpressure exerted by the choke. The pressure sensor **35***d* may be connected to an outlet of the mud pump **30***d* and may be operable to monitor standpipe pressure. The choke **36** may be fortified to operate in an environment where the return mixture **60***m* may include solids, such as cuttings. The choke **36** may include a hydraulic actuator operated by the PLC **75** via a hydraulic power unit (HPU) (not shown) to maintain backpressure (FIG. **2**A) in the wellhead **50**. Alternatively, the choke actuator may be electrical or pneumatic.

Each flow meter **34***b,d,r* may be a mass flow meter, such as a Coriolis flow meter, and may be in data communication with the PLC **75**. The flow meter **34***r* may be located downstream of the choke **36** and may be operable to monitor a flow rate of return mixture **60***m*. The flow meter **34***b* may be connected between the lift pump **30***b* and the lift tank **31***b* and may be operable to monitor a flow rate of the lift pump. The flow meter **34***d* may be connected between a mud pump **30***d* and the mud tank **31***d* and may be operable to monitor a flow rate of the mud pump.

Alternatively, the flow meters **34***b,d* may be volumetric instead of mass, such as a Venturi flow meter. Alternatively, a stroke counter (not shown) may be used to monitor a flow rate of each pump **30***b,d* instead of the respective flow meters **34***b,d*.

During the drilling operation, the mud pump **30***d* may pump drilling fluid **60***d* from the mud tank **31***d*, through the standpipe and a Kelly hose to the top drive **5**. The drilling fluid

31*d* may include a base liquid. The base liquid may be base oil, water, brine, seawater, or a water/oil emulsion. The base oil may be diesel, kerosene, naphtha, mineral oil, or synthetic oil. The drilling fluid 60*d* may further include solids dissolved and/or suspended in the base liquid, such as organophilic clay, lignite, and/or asphalt, thereby forming a mud. The lifting fluid 60*b* may be the base liquid of the mud and thus have a density less or substantially less than the drilling fluid 60*d* due to the weighting effect of the added solids.

The drilling fluid 60*d* may flow from the standpipe and into the drill string **10** via the top drive **5**. The drilling fluid 60*d* may be pumped down through the drill string **10** and exit the drill bit **15**, where the fluid may circulate the cuttings away from the bit and return the cuttings up an annulus **105** formed between an inner surface of the casing **52** or wellbore **100** and an outer surface of the drill string **10**. The returns 60*r* (drilling fluid 60*d* plus cuttings) may flow through the annulus **105** to the wellhead **50**. The lift pump 30*b* may pump lifting fluid 60*b* from the lift tank 31*b*, through the lift line **27**, and into the PCA 1*p* via a branch of the lower flow cross 41*b*.

In the PCA 1*p*, the lifting fluid 60*b* may mix with the returns 60*r* flowing from the wellhead **50**, thereby forming the return mixture 60*m*. The return mixture 60*m* may be diverted by the RCD **43** into the RCD outlet. The return mixture 60*m* may then flow to the MODU 1*m* via the return line **28**, through the choke **36** and flow meter 34*r*, and be processed by the shale shaker **33** to remove the cuttings. The return mixture 60*m* (minus cuttings) may be pumped flow from the shaker **33** to the centrifuge **32** by the transfer pump 30*t*. As the drilling fluid 60*d*, returns 60*r*, and return mixture 60*m* circulate, the drill string **10** may be rotated **16** by the top drive **5** and lowered by the traveling block **6**, thereby extending the wellbore **100** into the lower formation 104*b*.

The centrifuge **32** may include a housing, a feed tube, a bowl, a conveyor, a bowl drive, a conveyor drive, a low density (aka light) fluid outlet, and a high density (aka heavy) fluid outlet. The bowl may be disposed in the housing and rotatable relative thereto. The bowl may have a tapered end with the heavy fluid outlet and a non-tapered end with the light fluid outlet. The bowl may have a weir for blocking flow of the heavy fluid through the light fluid outlet. The weir may be adjustable. The conveyor may be a helical (aka screw) conveyor for pushing the heavier density fluid to the tapered end of the bowl and out of the heavy fluid outlet. The conveyor may have a channel formed therein for transporting the return mixture 60*m* (minus cuttings removed by the shaker **33**) from the feed tube into a chamber formed between the bowl and the conveyor. The conveyor may be rotated relative to the housing about a horizontal axis of rotation by the conveyor drive at a first speed and the bowl may be rotated relative to the housing along the same axis by the bowl drive at a second speed. The second speed may be greater than the first speed.

The return mixture 60*m* may enter the chamber of the centrifuge **32** via the feed tube and conveyor channel and be separated into layers of varying density by centrifugal forces such that the heavy fluid layer, such as drilling fluid 60*d*, is located radially outward relative to the horizontal axis and the light fluid layer, such as the lifting fluid 60*b*, is located radially inward relative to the heavy fluid layer. The weir may be set at a selected depth such that the drilling fluid 60*d* cannot pass over the weir and instead is pushed to the tapered end of the bowl and through the heavy fluid outlet by the rotating conveyor. The lifting fluid 60*b* may flow over the weir and through the light fluid outlet of the non-tapered end of the bowl. In this way, the return mixture 60*m* may be separated into its two (remaining) components: the drilling fluid 60*d* and the lifting fluid 60*b*. The drilling fluid 60*d* may be discharged from the heavy fluid outlet into mud tank 31*d* and the lifting fluid 60*b* may fluid may be discharged from the light fluid outlet into the lifting tank 31*b*.

Alternatively, the centrifuge may be omitted and the return mixture may be discharged into a waste tank instead of being recycled. Alternatively, the drill string may include casing instead of drill pipe and the casing may be left in the wellbore and cemented in place instead of removing the drill string to install a second casing string. Alternatively, the drill string **10** may include coiled tubing instead of drill pipe. Alternatively, the riser **25** may be omitted from the drilling system **1**.

FIG. **2**A illustrates operation of the PLC **75** during drilling of an ideal lower formation 104*b*. FIG. **2**B illustrates operation of the PLC **75** during drilling of a lower formation 104*b* having an abnormally high pressure region 110*p*. FIGS. **2**C and **2**D illustrate operation of the PLC **75** during drilling of a lower formation 104*b* having an abnormally low pressure region 110*f*.

The PLC **75** may be programmed to operate the lift pump 30*b* and the choke **36** so that a target bottomhole pressure (BHP) is maintained in the annulus **105** during the drilling operation. The target BHP may be selected to be within a drilling window defined as greater than or equal to a minimum threshold pressure, such as pore pressure, of the lower formation 104*b* and less than or equal to a maximum threshold pressure, such as fracture pressure, of the lower formation. As shown, the target pressure is an average of the pore and fracture BHPs.

Alternatively, the minimum threshold may be stability pressure and/or the maximum threshold may be leakoff pressure. Alternatively, threshold pressure gradients may be used instead of pressures and the gradients may be at other depths along the lower formation 130*b* besides bottomhole, such as the depth of the maximum pore gradient and the depth of the minimum fracture gradient. Alternatively, the PLC may be free to vary the BHP within the window during the drilling operation.

Due to the dual gradient effect caused by a substantially lower density (slope of Seawater line) of the sea **2** relative to the pore and fracture pressure gradients (slopes of Pore Pressure and Fracture Pressure lines, respectively) of the lower formation 104*b*, a single gradient drilling fluid would be unable to stay within the drilling window.

A static density of the drilling fluid 60*d* (typically assumed equal to returns 60*r*; effect of cuttings typically assumed to be negligible) may correspond to a minimum threshold pressure gradient of the lower formation 104*b*, such as being greater than or equal to a pore pressure gradient. An equivalent circulation density (ECD) (static density plus dynamic friction drag) of the drilling fluid 60*d* may correspond to a maximum threshold pressure gradient of the lower formation 104*b*, such as fracture pressure gradient.

A static and/or ECD of the lifting fluid 60*b* may be less than, substantially less than, or equal to a density of seawater **2** (eight point five six pounds per gallon (PPG) or one thousand twenty-five kilograms per cubic meter (kg/m^3)). The lifting fluid 60*b* may compensate for the dual gradient effect by creating a corresponding dual gradient effect by reducing or substantially reducing the static density and/or ECD of the returns 60*r* to a static density and/or ECD of the return mixture 60*m*. The static and/or ECD of the return mixture 60*m* may correspond to the seawater density. The lifting fluid 60*b* may reduce the static density/ECD of the returns 60*r* by a lifting ratio (static density/ECD of return mixture 60*m* divided by static density/ECD of returns 60*r*) of less than one, such as one-half to three-fourths.

During the drilling operation, the PLC **75** may execute a real time simulation of the drilling operation in order to predict the actual BHP from measured data, such as standpipe pressure from sensor **35***d*, mud pump flow rate from flow meter **31***d*, lifting fluid flow rate from flow meter **34***b*, wellhead pressure from sensor **47***b*, and return fluid flow rate from flow meter **34***r*. The PLC **75** may then compare the predicted BHP to the target BHP and adjust the choke **36** accordingly.

During the drilling operation, the PLC **75** may also perform a mass balance to monitor for a kick or lost circulation. As the drilling fluid **60***d* is being pumped into the wellbore **100** by the mud pump **30***d*, the lifting fluid **60***b* is being pumped into the PCA **1***p* by the lifting pump **30***b*, and the return mixture **60***m* is being received from the return line **28**, the PLC **75** may compare the mass flow rates (i.e., sum of drilling and lifting fluid flow rates minus return mixture flow rate) using the flow meters **34***b,d,r*. The PLC **75** may use the mass balance to monitor for instability of the lower formation **104***b*, such as formation fluid **106** entering the annulus **105** (FIG. **2**B) and contaminating **61***r* the returns **60***r* or returns **60***r* entering the formation **104***b* (FIG. **2**C).

Upon detection of instability, the PLC **75** may take remedial action, such as tightening the choke **36** (compare Back Pressure in FIG. **2**A to same in FIG. **2**B) in response to detection of formation fluid **106** entering the annulus **105** and relaxing the choke (compare Back Pressure in FIG. **2**A to absence of same in FIG. **2**C) in response to returns **60***r* entering the formation **104***b*. The PLC **75** may further divert the contaminated return mixture **61***m* into a degassing spool in response to detection of fluid ingress.

The degassing spool may include automated shutoff valves at each end, a mud-gas separator (MGS) **432** (FIG. **2**B), and a gas detector. A first end of the degassing spool may be connected to the returns line **28** between the returns flow meter **34***r* and the shaker **33** and a second end of the degasser spool may be connected to an inlet of the shaker. The gas detector may include a probe having a membrane for sampling gas from the return mixture **60***m*, a gas chromatograph, and a carrier system for delivering the gas sample to the chromatograph. The MGS **432** may include an inlet and a liquid outlet assembled as part of the degassing spool and a gas outlet connected to a flare or a gas storage vessel.

Referring specifically to FIGS. **2**C and **2**D, relaxing of the choke **36** by the PLC **75** has instantaneously (i.e., less than or equal to twenty seconds) negotiated narrowing of the drilling window caused by the low pressure region **110***f* so that the drilling operation may continue without interruption. However, for the particular lower formation **104***b* shown, the actual BHP remains near the maximum threshold, leaving little or no margin. The PLC **75** may then reset the target BHP to be in a middle of the narrowed drilling window, and may increase a flow rate of the lifting pump **30***b* to achieve the target BHP. In contrast to the instantaneous response of operating the choke **36**, the response of the actual BHP may be gradual (i.e., greater than or equal to twenty minutes). The gradual harmonization of the actual and target BHPs may be inconsequential as the drilling operation may be ongoing. The increase in the lifting fluid pump flow rate may be monotonic or gradual.

Alternatively, the PLC **75** may increase a flow rate of the lifting pump **30***b* while tightening the choke **36** in response to detection of fluid egress into the lower formation **104***b*. The flow rate increase may be monotonic or gradual and the choke tightening may be monotonic or gradual.

An analogous situation may occur for the fluid ingress scenario of FIG. **2**B should the required tightening of the choke **36** create backpressure exceeding the design pressure of the RCD **43** (see FIG. **5** and discussion thereof below). In this instance, the PLC **75** may tighten the choke **36** to the RCD maximum pressure to instantaneously negotiate the high pressure region **110***p* while leaving little or no margin and then the PLC **75** may decrease the lifting pump flow rate to gradually improve the margin.

Alternatively, the PLC **75** may decrease a flow rate of the lifting pump **30***b* while relaxing the choke **36** in response to detection of fluid ingress to the annulus. The flow rate decrease may be monotonic or gradual and the choke relaxing may be monotonic or gradual. Alternatively, the riser **25** design pressure may be less than the RCD design pressure such that the riser is the weak point in the drilling system **1**. Alternatively, the lower formation **104***b* may be drilled underbalanced and some ingress may be tolerated.

Alternatively, the PLC **75** may include other factors in the mass balance, such as displacement of the drill string **10** and/or cuttings removal. The PLC **75** may calculate a rate of penetration (ROP) of the drill bit **15** by being in communication with the drawworks **9** and/or from a pipe tally or a mass flow meter may be added to the cuttings chute of the shaker **33** and the PLC **75** may directly measure the cuttings mass rate. Additionally, the PLC **75** may monitor for other instability issues, such as differential sticking and/or collapse of the wellbore **100** by being in data communication with the top drive **5** for receiving torque exerted by the top drive and/or angular speed of the quill.

Should adjusting the choke **36** fail to restore pressure control of the wellbore, the PLC **75** may take emergency action, such as halting drilling (rotation of drill string, mud and lifting pumps), closing annular BOP **42***a*, and opening kill valve **45***a* in response to fluid ingress or halting drilling (rotation of drill string and mud pump), closing annular BOP, and maintaining or increasing pumping of the lifting fluid in response to fluid egress.

FIG. **3**A illustrates a portion of an UMRP **220** of an offshore drilling system **201**, according to another embodiment of the present invention. FIG. **3**B illustrates a PCA **201***p* of the drilling system **201**. The drilling system **201** may include the MODU **1***m*, the drilling rig **1***r*, the fluid handling system **1***h*, a fluid transport system **201***t*, and a PCA **201***p*. The PCA **201***p* may be similar to the PCA **1***p* except that the RCD **43** and kill line **44** (and associated components) have been omitted. The fluid transport system **201***t* may be similar to the fluid transport system **1** except for the addition of an RCD **243** to the UMRP **220**, connection of a lower end of the lift line **27** to an inlet of the RCD **243** instead of to the lower flow cross **41***b*, and the addition of one or more pressure sensors **247***a,b*.

The RCD **243** may be similar to the RCD **43** except for connection of the bearing assembly to the housing using a latch instead of a packing and orientation of both stripper seals to seal against the drill pipe **10***p* in response to higher pressure in the riser **25** than the UMRP **220** (components thereof above the RCD). The RCD housing may be connected to the upper end of the riser **25** and a lower end of the slip joint **23**. The RCD housing may also be submerged adjacent the waterline **2***s*. The pressure sensor **247***a* may be connected to the lift line **27** between the check valve **46** and the RCD inlet and pressure sensor **247***b* may be connected to an upper housing section of the RCD **243** above the bearing assembly. The pressure sensors **247***a,b* may be in data communication with the PLC **75** and the RCD latch piston may be in fluid communication with the HPU of the PLC **75** via an interface of the RCD and RCD umbilical **270**.

Alternatively, the RCD **243** may be located above the waterline **2***s* and/or along the UMRP **220** at any other location besides a lower end thereof. Alternatively, the RCD **243** may be located at an upper end of the UMRP **220** and the slip joint **23** and bracket connecting the UMRP to the rig may be omitted or the slip joint may be locked instead of being omitted.

The drilling operation conducted using the drilling system **201** may be similar to that conducted using the drilling system **1** except for the flow path of the lifting fluid **60***b*. The lifting fluid **60***b* may be injected into a top of the riser **25** via the RCD inlet and flow down the riser until the lifting fluid collides **260** with the returns **60***r* flowing upwardly from the wellbore **100**, thereby forming the return mixture **60***m*. Should the lower formation **104***b* kick gas **106**, the downward flow of the lifting fluid **60***b* may discourage the gas from separating from the contaminated returns **61***r* and floating up past the collision zone **260** into the riser **25** and instead encourage the gas to flow into the outlet of the upper flow cross **41***u* as part of the contaminated return mixture **61***m*.

Alternatively, the lifting fluid **60***b* may be injected into the PCA **201***p* and the return mixture **60***m* may flow up the riser **25** and be diverted from an outlet of the RCD **243**. Additionally, for this alternative, the lift line **27** may be connected to the riser **25** at various points therealong for selective location of mixing (FIG. **5**).

FIG. **4**A illustrates a portion of an UMRP **320** of an offshore drilling system **301**, according to another embodiment of the present invention. FIG. **4**B illustrates a portion of a concentric marine riser **325** of the drilling system **301**. FIG. **4**C illustrates connection of the concentric riser **325** to the PCA **201***p*.

The drilling system **301** may include the MODU **1***m*, the drilling rig **1***r*, the fluid handling system **1***h*, a fluid transport system **301***t*, and the PCA **201***p*. The fluid transport system **301***t* may include the drill string **10**, the UMRP **320**, the concentric riser **325**, the lift line **27**, and the return line **28**. The UMRP **320** may include a diverter (not shown, see **21**), a flex joint (not shown, see **22**), the slip joint **23**, the (outer) tensioner **24**, the RCD **243**, an inner tensioner **324**, a seal head **342**, a flow cross **341**, and a riser compensator **380**. The UMRP components may be connected together, such as by flanged connections.

The concentric riser **325** may include an inner riser string **326** concentrically disposed within an outer riser string **327** such that an outer annulus **305***o* is defined between the riser strings. The drill string **10** may extend through the inner riser string **326** such that an inner annulus **305***i* is defined between the drill string and the inner riser string. The inner riser string **326** may include a hanger **326***h*, a piston **326***p*, joints of riser pipe **326***r* connected together, such as by threaded connections, and a shoe **326***s*. The piston **326***p* and the shoe **326***s* may each be connected to a respective end of the inner riser pipe **326***r*, such as by a threaded connection. The outer riser string **327** may include end connectors, joints of riser pipe **327***r* connected together, such as by threaded connections, and one or more anchors **327***a-c*. Each end connector may be a flange connected to the respective end of the outer riser pipe, such as by a threaded connection. Each anchor **327***a-c* may be interconnected with the outer riser pipe **327***p*, such as by a threaded connection. The anchors **327***a-c* may be spaced along at least a portion of the outer riser string **327**, such as along a mid and lower portion thereof (i.e., lower two-thirds).

The inner riser shoe **326***s* may include an annular body carrying one or more detents, such as drag blocks (only one shown), and a packer. The drag blocks may be spring-loaded and adapted to engage a detent profile, such as a groove, formed in an inner surface of each anchor **327***a-c*. Each anchor **327***a-c* may include a housing and a latch. The shoe packer may include an actuator ring disposed in a recess formed in an outer surface of the inner riser shoe. The actuator ring may be a two-part member having a groove formed in an outer surface thereof operable to receive one or more fasteners, such as dogs (only one shown), of each anchor latch. Engagement of the drag blocks with the respective anchor locator groove may occur when the actuator ring and the respective anchor latch dogs are aligned. Each anchor latch dog may be pushed into the actuator groove by a wedge of a respective anchor actuator. Each anchor actuator may further include a hydraulically operated piston and cylinder assembly. Each anchor wedge may be connected to a piston of the assembly by a rod. Engagement of the respective anchor dogs with the actuator ring may longitudinally connect the inner riser shoe **326***s* and the respective anchor **327***a-c*.

The riser shoe packer may further include a seal assembly having a packing straddled by backup rings and disposed in the shoe body recess. The seal assembly and actuator ring may interact such that when the respective anchor dogs are in a locking position with the shoe actuator ring groove, the shoe packing will be longitudinally compressed by action of the dogs driving the actuator ring members apart. Radial expansion of the shoe packing may result from compression thereof and the expanded packing may seal against an inner surface of a housing of the respective anchor **327***a-c*. Each anchor housing may have a shallow groove formed in an inner surface thereof for receiving the shoe packing.

The riser shoe body may further have a flow passage formed therethrough and a check valve. The shoe flow passage may provide fluid communication between the outer annulus **305***o* and the inner annulus **305***i*. The shoe check valve may be disposed in the passage and oriented to allow flow of the lifting fluid **60***b* through the passage from the outer annulus **305***o* to the inner annulus **305***i* and to prevent reverse flow of the returns **60***r* through the passage from the inner annulus to the outer annulus.

The hanger **326***h* may include an annular body having an upper portion carrying a first packer, a mid sleeve portion, and a lower portion carrying a second packer. The tensioner **324** may include a housing having an upper latch profile section, a mid sleeve section, and a lower latch section. The hanger second packer and the tensioner lower latch may include similar components and interact in a similar fashion to the riser shoe packer and the respective anchor latch. The hanger first packer may include one or more fasteners, such as keys (only one shown), and the tensioner latch profile may be a keyway operable to receive the keys. The hanger body may have a recess formed in an outer surface thereof and the keys may be spring-loaded into a key ring disposed in the recess. The hanger first packer may further include a packing disposed in the recess. Engagement of the keys and the keyways may longitudinally support the key ring from the tensioner such that continued longitudinal movement of the hanger relative to the tensioner may compress the hanger first packing into engagement with the upper tensioner housing section.

An outer hydraulic chamber may be formed between the hanger sleeve portion and the tensioner sleeve portion and isolated by the hanger packers. The tensioner sleeve portion may have a hydraulic port providing fluid communication between the outer chamber and the RCD umbilical **270**. The hanger sleeve may have a hydraulic port providing fluid communication between the outer hydraulic chamber and a variable inner hydraulic chamber. The inner chamber may be formed between the inner riser pipe **326***r* and the hanger sleeve portion and isolated by the piston **326***p* and one or more seals carried by the hanger body lower portion. To account for changes in length of the inner riser **326** relative to the outer riser **327** due to variations in temperature, pressure, and/or loading, the inner riser may be tensioned by controlling the supply of hydraulic fluid to the hydraulic chambers. The hydraulic fluid may exert an upward force against the piston **326***p*, thereby tensioning the inner riser **326**.

The riser compensator **380** may be employed to prevent fluid displacement caused by operation of the tensioner **324** from affecting the mixture flow meter **34***r*. The riser compensator **380** may include an accumulator **381**, a gas source **382**, a pressure regulator **383**, a flow line **384**, one or more shutoff valves **385**, **388**, and the pressure sensor **247***a*.

The shutoff valve **385** may be automated and have a hydraulic actuator (not shown) operable by the PLC **75** via fluid communication with the HPU. The shutoff valve **385** may be connected to a port of the RCD **243** and the flow line **384**. The flow line **384** may be a flexible conduit, such as hose, and may also be connected to the accumulator **381** via a flow tee. The accumulator **381** may store only a volume of compressed gas, such as nitrogen. Alternatively, the accumulator may store both liquid and gas and may include a partition, such as a bladder or piston, for separating the liquid and gas. A liquid and gas interface **387** may be in the flow line **384**. The shutoff valve **388** may be disposed in a vent line of the accumulator **381**. The pressure regulator **383** may be connected to the flow line **384** via a branch of the tee. The pressure regulator **383** may be automated and have an adjuster operable by the PLC **75** via fluid communication with the HPU or electrical communication with the PLC. A set pressure of the regulator **383** may correspond to a set pressure of the choke **36** and both set pressures may be adjusted in tandem. The gas source **382** may also be connected to the pressure regulator **383**.

The riser compensator **380** may be activated by opening the shutoff valve **385**. During expansion of the inner riser **326**, the volume of fluid displaced by the upward movement may flow through the shutoff valve **385** into the flow line **384**, moving the liquid and gas interface **387** toward the accumulator **381** and accommodating the upward movement. The interface **387** may or may not move into the accumulator **381**. During contraction of the inner riser **326**, the interface **387** may move along the flow line **384** away from the accumulator **381**, thereby replacing the volume of fluid moved thereby. Alternatively, the riser compensator may be omitted and the PLC **75** may adjust the measurement by the mixture flow meter **34***r* based on hydraulic fluid flow to the tensioner **324**.

The lift line **27** may be connected to a branch of the flow cross **341**. A pressure sensor **347** may be connected to the lift line **27** between the check valve **46** and the flow cross **341**. The flow cross **341** may provide fluid communication between the lift line **27** and the outer annulus **305***o*. The pressure sensor **347** may be in data communication with the PLC **75**. The flow cross **341** may be connected to the upper end connector of the outer riser **327**. The seal head **342** may be connected to the flow cross **341**. The seal head **342** may be an annular BOP including a housing, a packing, and a piston. The housing may have one or more hydraulic ports providing fluid communication between the PLC HPU and respective hydraulic chambers formed between the piston and the housing. The piston may be operated to longitudinally compress the packing into radial engagement against an outer surface of the inner riser pipe, thereby isolating a top of the outer annulus **305***o*.

The drilling operation conducted using the drilling system **301** may be similar to that conducted using the drilling system **1** except for the flow paths of the lifting fluid **60***b* and the return mixture **60***m*. The lifting fluid **60***b* may be injected into a top of the outer annulus **305***o* via the flow cross **341** and flow down the outer annulus. The lifting fluid **60***b* may continue into the inner riser shoe passage and through the check valve and may mix with the returns **60***r* at a bottom of the inner annulus **305***i*, thereby forming the return mixture **60***m*. The return mixture **60***m* may flow up the inner annulus **305***i* to the UMRP **320**. The return mixture **60***m* may continue through the UMRP **320** until reaching the RCD **243**. The RCD **243** may divert the return mixture **60***m* into an outlet thereof and into the return line **28** connected thereto.

FIG. **5** illustrates selection of a location of the inner riser shoe **326***s*. The lower formation **104***b* may have a narrow drilling window. Attempting to drill the lower formation **104***b* using the inner riser shoe **326***s* connected to the lower anchor **327***c* (illustrated by dashed line) would require backpressure exceeding the RCD design pressure (aka maximum). Connecting the inner riser shoe **326***s* to the upper anchor **327***a* reduces the required back pressure due to the increased hydrostatic pressure exerted by the increased length of the returns column (solid line) before density reduction by the lifting fluid **60***b*. The reduction in required backpressure allows for drilling of the lower formation **104***b* within the capability of the RCD **243**. Shoe location selection and installation of the inner riser **326** may occur before commencement of the drilling operation.

Should the lower formation **104***b* kick gas **106**, presence of the inner riser **326** in at least the upper portion of the outer riser **327** may serve to increase the pressure rating of the concentric riser **325** due to the reduced diameter of the inner riser. A wall thickness of the inner riser may also be increased relative to the outer riser. Further, the inner annulus **305***i* may also serve as a choked passage to limit the flow of gas therethrough.

FIGS. **6**A and **6**B illustrate an offshore drilling system **401**, according to another embodiment of the present invention. The drilling system **401** may include the MODU **1***m*, the drilling rig **1***r*, the fluid handling system **401***h*, a riserless fluid transport system **401***t*, and a riserless PCA **401***p*. The drilling system **401** may employ lifting fluid **460**, such as a gas, (i.e., nitrogen) or gaseous mixture (i.e., mist or foam).

The fluid handling system **401***h* may include the mud pump **30***d*, a lift vessel **431**, a fluid separator, such as a mud-gas separator **432**, the shale shaker **33**, the flow meter **34***d*, a flow control valve **433**, one or more pressure sensors **35***d*, **435***b,t*, a transfer compressor **437**, and a nitrogen production unit (NPU) **438**. The NPU **438** may include an air compressor, a cooler, a demister, a heater, a particulate filter, a membrane, and a booster compressor. The air compressor may receive ambient air and discharge compressed air to the cooler. The cooler, demister, and heater may condition the air for treatment by the membrane. The membrane may include hollow fibers which allow oxygen and water vapor to permeate a wall of the fiber and conduct nitrogen through the fiber. An oxygen probe (not shown) may monitor and assure that the produced nitrogen meets a predetermined purity. The booster compressor may compress the nitrogen exiting the membrane for storage in the lift tank **431**.

Each pressure sensor **35***d*, **435***b,t* may be in data communication with the PLC **75**. The pressure sensor **435***t* may be connected to the lift tank **431**. The PLC **75** may monitor the pressure in the lift tank **431** and activate the NPU **438** should the lift tank need charging. The pressure sensor **435***b* may be connected to the lift line **27** downstream of the flow control valve **433**. The flow control valve **433** may be connected to an outlet of the lift tank **431** and the lift line **27** may be connected to the flow control valve. The lift line **27** may extend from the MODU **1***m* to a mixing manifold **440** of the PCA **401***p*. The PLC **75** may monitor and control the flow rate of lifting fluid

460*b* transported through the lift line **27** using the flow control valve **433**. The flow control valve **433** may include an adjustable orifice or Venturi throat and an actuator for adjusting the orifice/throat. The actuator may be operated by the PLC **75** via hydraulic communication with the HPU. Alternatively, the actuator may be electric or pneumatic. The lift tank **431** may be maintained at a pressure sufficiently greater than a pressure of the mixing manifold **440** for sonic flow through the flow control valve **433**. The PLC **75** may then calculate the mass flow rate of lifting fluid **460***b* using the orifice/throat area of the flow control valve **433**.

The riserless fluid transport system **401***t* may include the drill string **10**, the lift line **27**, and the return line **28**. The riserless PCA **401***p* may include the wellhead adapter **40**, one or more flow crosses **41***u,b*, one or more blow out preventers (BOPs) **42***a,u,b*, the RCD **243**, the control pod **76**, one or more accumulators (not shown), a subsea flow meter **434**, a subsea choke **436**, and the mixing manifold **440**. Alternatively, the RCD **43** may be used instead of the RCD **243**.

The subsea flow meter **434**, subsea choke **436**, and pressure sensors **447***a,b* may be assembled as part of the mixing manifold **440**. The subsea flow meter **434** may be a mass flow meter, such as a Coriolis flow meter, and may be in data communication with the PLC **75** via the pod **76** and the umbilical **70**. The subsea flow meter **434** may be located in the mixing manifold **440** adjacent to the RCD outlet and may be operable to monitor a flow rate of the returns **60***r*. The subsea choke **436** may be located in the mixing manifold **440** between the subsea flow meter **434** and the lifting line **27**. The subsea choke **436** may be fortified to operate in an environment where the returns **60***r* may include solids, such as cuttings. The subsea choke **436** may include a hydraulic actuator operated by the PLC HPU (via the pod **76** and the umbilical **70**) to maintain backpressure in the wellhead **50**.

Alternatively, a subsea volumetric flow meter may be used instead of the mass flow meter. Alternatively, the choke actuator may be electrical or pneumatic. Alternatively, the MODU choke **36** may be used instead of the subsea choke **436**.

The mixing manifold **440** may be connected to the RCD outlet, the lift line **27**, and the return line **28**. The pressure sensors **447***a,b* may be located in the mixing manifold **440** in a position straddling the subsea choke **436**. Each pressure sensor **447***a* may be in data communication with the PLC **75** via the pod **76** and the umbilical **70**. The return line **28** may extend from the mixing manifold **440** to an inlet of the MGS **432** onboard the MODU **1***m*. The MGS **432** may be vertical, horizontal, or centrifugal and may be operable to separate the lifting fluid **460***b* from the return mixture **460***m*. The separated lifting fluid **460***b* may be supplied an inlet of the booster compressor **437**. The booster compressor **437** may discharge the separated lifting fluid **460***b* to the lift vessel **431**. Alternatively, the separated lifting fluid may be flared or vented to atmosphere. The separated returns **60***r* may be supplied to the shale shaker **33**.

The drilling operation conducted using the drilling system **401** may be similar to that conducted using the drilling system **1** except for the gaseous lifting fluid **460***b*, the flow paths of the lifting fluid **460***b* and the return mixture **460***m*, and the mass balance monitoring by the PLC **75**. The returns **60***r* may flow from the wellbore **100**, through the wellhead **50** and into the PCA **401***p*. The returns **60***r* may continue through the PCA **401***p* and be diverted by the RCD **243** into an outlet thereof. The returns **60***r* may continue through the subsea mass flow meter **434** and the subsea choke **436** and into a mixing chamber of the manifold **440**. Since the mass flow rate of the returns **60***r* may be measured upstream of mixing, the need for the lifting fluid flow rate for the PLC **75** to perform the mass balance may be obviated.

The lifting fluid **460***b* may be injected into lift line **27** from the lift vessel **431**. The lifting fluid **460***b* may continue through the check valve **46** and may mix with the returns **60***r* in the mixing manifold **440**, thereby forming the return mixture **460***m*. The return mixture **460***m* may flow up the return line **28** to the MGS **432** for recycling thereof.

Alternatively, the lift line **27** may be connected to the return line **28** at various points therealong for selective location of mixing (FIG. **5**). Alternatively, a riser may be added to the drilling system **401** for barrier fluid (FIG. **1**B). Alternatively, a riser may be added to the drilling system **401**, the RCD **243** located in the UMRP, and the lifting fluid **460***b* injected down the riser instead of the lift line **27** for counter-flow mixing (FIG. **3**B). In this counter-flow alternative, the mixture **460***m* would flow through the subsea flow meter **434** and choke **436** instead of the returns **60***r*. Alternatively, the lifting fluid **60***b* may be used with the drilling system **401** instead of the lifting fluid **460***b*.

FIG. **6**C illustrates a lubricator **450** for use with the drilling system **401**. The PCA **401***p* may further include the lubricator **450** connected to a top of the RCD **243**, such as by a flanged connection. The lubricator **450** may include a shutoff valve **451**, a tool housing **452**, a flow cross **453**, a seal head **454**, and a landing guide **455**. The lubricator components **451**-**455** may each include a housing having a longitudinal bore therethrough and may each be connected, such as by flanges, such that a continuous bore is maintained therethrough. The bore may have drift diameter, corresponding to a drift diameter of the wellhead **50**. The tool housing **452** may have a length corresponding to a combined length of the BHA **10***b* and the RCD bearing assembly **243***r*. The seal head **454** may be similar to the seal head **352**. A branch of the flow cross **453** may be connected to a waste tank or waste treatment equipment (not shown) onboard the MODU **1***m* by a waste line **428**. A shutoff valve **445** may be disposed in the waste line **428**.

Each shutoff valve **445**, **451** may be automated and have a hydraulic actuator operable by the control pod **76** via a jumper **470**. Alternatively, the valve actuators may be electrical or pneumatic. The waste line valve **445** may be normally closed and the housing valve **451** may be normally open during the drilling operation. The seal head **454** may normally be disengaged from the drill pipe **10***p* during the drilling operation. The seal head piston may also be operated by the control pod **76** via the jumper **470**.

The lubricator **450** may be used to wash the BHA **10***b* and the bearing assembly **243***r* during tripping of the drill string **10** to the MODU **1***m* after drilling the lower formation **104***b* has been completed or if maintenance of the BHA **10***b* or RCD **243** needs to be performed. The drill string **10** may be retrieved from the wellbore **100** until the BHA **10***b* reaches the PCA **401***p*. Once the BHA **10***b* is proximate to the RCD **243**, the bearing assembly **243***r* may be released from the RCD housing. The BHA **10***b* may then carry the bearing assembly **243***r* as retrieval of the drill string **10** continues. Once the BHA **10***b* and bearing assembly **243***r* are located in the tool housing **452**, the housing shutoff valve **451** may be closed, the seal head **454** engaged with the drill pipe **10***p*, and the waste line valve **445** opened.

Wash fluid **460***w* may be pumped down the drill string **10** and exit the drill bit **15**. The wash fluid **460***w* may be environmentally compatible, such as seawater, hydrates inhibitor, or a mixture of the two. The wash fluid **460***w* may flush drilling fluid **60***d* from the drill string **10** and wash return residue from the BHA **10***b* and the bearing assembly **243***r*. The spent wash fluid **461***w* may be discharged from the tool housing **452** into the waste line **428** via the flow cross branch. The spent wash fluid **461***w* may continue to the MODU **1***m* via the waste line **428** for treatment or disposal. Once the washing operation is complete, the seal head **454** may be disengaged from the drill pipe **10***p* and the waste line valve **445** closed. Retrieval of the drill string **10** to the MODU **1***m* may then continue.

Alternatively, the housing shutoff valve **451** may be omitted and one of the BOPs **42***a,u,b* closed instead to wash the BHA.

FIG. **6**D illustrates an alternative PCA **471***p* for use with the drilling system **401**. The PCA **471***p* may be similar to the PCA **401***p* except that the locations of the subsea choke **436** and subsea flow meter **434** in the mixing manifold **440** have been switched and a choke bypass line has been connected to the mixing manifold **447***a* and flow crosses **41***u,b*.

FIGS. **7**A and **7**B illustrate an offshore drilling system, according to another embodiment of the present invention. The drilling system **501** may include the MODU **1***m*, the drilling rig **1***r*, the fluid handling system **501***h*, a fluid transport system **501***t*, and a PCA **501***p*. The fluid handling system **501***h* may include the pumps **30***b,d,t*, the fluid tanks **31***b,d*, the centrifuge **32**, the shale shaker **33**, the pressure sensor **35***d*, and a return line **528**. A first end of the return line **528** may be connected to an outlet of the diverter **21** and a second end of the return line **528** may be connected to an inlet of the shaker **33**.

The PCA **501***p* may include the wellhead adapter **40**, the flow crosses **41***u,b*, a flow cross **541**, the BOPs **42***a,u,b*, the RCD **243**, the control pod **76**, the accumulators, the LMRP, a subsea flow meter **434**, a subsea choke **436**, a bypass spool **540**, and the receiver **546**. Alternatively, the RCD **43** may be used instead of the RCD **243**. The fluid transport system **501***t* may include the drill string **10**, the UMRP **20**, the marine riser **25**, and the lift line **27**.

The flow cross **541** may be connected to the receiver **546** and to an upper end of the RCD **243**. The bypass line **540** may be connected to the RCD outlet and a branch of the flow cross **541**. A lower end of the lift line **27** may also be connected to a branch of the flow cross **541**. The pressure sensors **447***a,b* may be located in the bypass line **540** in a position straddling the subsea choke **436**. Each pressure sensor **447***a* may be in data communication with the PLC **75** via the pod **76** and the umbilical **70**. The subsea flow meter **434** subsea choke **436**, and pressure sensors **447***a,b* may be assembled as part of the bypass line **540**. The subsea flow meter **434** may be located in the bypass line **540** adjacent to the RCD outlet and may be operable to monitor a flow rate of the returns **60***r*. The subsea choke **436** may be located in the bypass line downstream of the flow meter **434**.

Alternatively, the locations of the flow meter **434** and choke **436** in the bypass spool **540** may be switched. Alternatively, a subsea volumetric flow meter may be used instead of the mass flow meter. Alternatively, the choke actuator may be electrical or pneumatic. Alternatively, the MODU choke **36** may be used instead of the subsea choke **436**.

The drilling operation conducted using the drilling system **501** may be similar to that conducted using the drilling system **1** except for the flow paths of the lifting fluid **60***b* and the return mixture **60***m* and the mass balance monitoring by the PLC **75**. The returns **60***r* may flow from the wellbore **100**, through the wellhead **50** and into the PCA **501***p*. The returns **60***r* may continue through the PCA **501***p* and be diverted by the RCD **243** into the bypass line **540**. The returns **60***r* may continue through the subsea mass flow meter **434** and the subsea choke **436** and exit the bypass line into an upper portion of the PCA **501***p*. Since the mass flow rate of the returns **60***r* may be measured upstream of mixing, the need for the lifting fluid flow rate for the PLC **75** to perform the mass balance may be obviated.

The lifting fluid **60***b* may be injected into the lift line **27** by the lift pump **30***b*. The lifting fluid **60***b* may continue through the check valve **46** and may mix with the returns **60***r* in the PCA upper portion, thereby forming the return mixture **60***m*. The return mixture **60***m* may flow up the riser **25** to the diverter **21**. The return mixture **60***m* may flow into the return line **528** via the diverter outlet. The returns may continue through to the shale shaker **33** and be processed thereby to remove the cuttings.

Alternatively, the lift line **27** may be connected to the riser **25** at various points therealong for selective location of mixing (FIG. **5**). Alternatively, the mixing manifold **440** and return line **28** may be used instead of the return line **528** and the bypass spool **540** and the riser **25** used for barrier fluid (FIG. **1**B) or omitted. Alternatively, the RCD **243** may be located in the UMRP and the lifting fluid **60***b* injected down the riser **25** instead of the lift line **27** for counter-flow mixing (FIG. **3**B). In this counter-flow alternative, the mixture **60***m* would flow through the subsea flow meter **434** and choke **436** instead of the returns **60***r*.

Alternatively, the subsea flow meter **434** and/or subsea choke **436** may be used in any of the other drilling systems **1**, **201**, **301** instead of the respective MODU flow meter **34***r* and/or MODU choke **36**. Alternatively, the gaseous lifting fluid **460***b* may be used in any of the other drilling systems **1**, **201**, **301**, **501** instead of the lifting fluid **60***b*.

While the foregoing is directed to embodiments of the present invention, other and further embodiments of the invention may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

The invention claimed is:

1. A method of drilling a subsea wellbore, comprising:

drilling the wellbore by injecting drilling fluid through a tubular string extending into the wellbore from an offshore drilling unit (ODU) and rotating a drill bit disposed on a bottom of the tubular string,

wherein:

the drilling fluid exits the drill bit and carries cuttings from the drill bit, and

the drilling fluid and cuttings (returns) flow to a floor of the sea via an annulus defined by an outer surface of the tubular string and an inner surface of the wellbore, and

while drilling the wellbore:

mixing lifting fluid with the returns at a flow rate proportionate to a flow rate of the drilling fluid, thereby forming a return mixture,

wherein:

the lifting fluid has a density substantially less than a density of the drilling fluid, and

the return mixture has a density substantially less than the drilling fluid density;

measuring a flow rate of the returns or the return mixture;

comparing the measured flow rate to the drilling fluid flow rate to ensure control of a formation being drilled; and

adjusting the lifting fluid flow rate in response to the comparison.

2. The method of claim **1**, wherein the returns flow from the seafloor, through a subsea wellhead, and into a pressure control assembly (PCA) connected to the subsea wellhead.

3. The method of claim 2, wherein:
the lifting fluid is mixed with the returns in the PCA, and
the return mixture flows from the PCA to the ODU via a conduit.

4. The method of claim 3, wherein the lifting fluid is injected into the PCA through a first auxiliary line.

5. The method of claim 4, wherein the conduit is a second auxiliary line.

6. The method of claim 4, wherein the conduit is a marine riser.

7. The method of claim 2, wherein:
a marine riser is connected to the PCA and connected to the ODU by an upper marine riser package (UMRP),
the lifting fluid is mixed with the returns by injection into the UMRP and down the marine riser, and
the return mixture flows to the ODU via a conduit.

8. The method of claim 7, wherein the conduit is an auxiliary line.

9. The method of claim 7, wherein:
the marine riser is an outer riser,
an inner riser is disposed in the outer riser and extends from the UMRP toward the PCA along at least a portion of the outer riser,
the lifting fluid is transported down an outer annulus formed between the risers,
the lifting fluid is mixed with the returns at a shoe of the inner riser, and
the conduit is an inner annulus formed between the inner riser and the tubular string.

10. The method of claim 9, further comprising selectively locating the inner riser shoe along the outer riser.

11. The method of claim 2, wherein:
the lifting fluid is mixed with the returns in a conduit extending from the PCA to the ODU, and
the lifting fluid is injected into the conduit through an auxiliary line.

12. The method of claim 11, further comprising selectively locating an injection point of the lifting fluid along the conduit.

13. The method of claim 1, wherein the flow rate is measured using a subsea mass flow meter.

14. The method of claim 1, wherein:
the measured flow rate is the return mixture flow rate,
the flow rate is measured using a mass flow meter located onboard the ODU, and
the lifting fluid flow rate is included in the comparison.

15. The method of claim 1, wherein the measured flow rate is the returns flow rate.

16. The method of claim 1, wherein:
the returns or the return mixture flows through a variable choke valve, and
the method further comprises adjusting the variable choke valve in response to the comparison.

17. The method of claim 16, wherein:
the return mixture flows through the variable choke valve, and
the variable choke valve is located onboard the ODU.

18. The method of claim 16, wherein the variable choke valve is located subsea.

19. The method of claim 18, wherein the returns flow through the subsea variable choke valve.

20. The method of claim 18, wherein the return mixture flows through the subsea variable choke valve.

21. The method of claim 1, wherein:
drilling fluid is mud, and
the lifting fluid is base liquid of the mud.

22. The method of claim 21, wherein:
the mud is oil based, and
the method further comprises separating the return mixture into the mud and base oil and recycling the separated mud and base oil while drilling the wellbore.

23. The method of claim 1, wherein:
the lifting fluid density is less than a density of seawater, and
the return mixture density corresponds to the seawater density.

24. The method of claim 1, wherein the return mixture density is one-half to three-fourths of the drilling fluid density.

25. The method of claim 1, wherein the lifting fluid is gaseous.

26. A method of drilling a subsea wellbore, comprising:
drilling the wellbore by injecting drilling fluid through a tubular string extending into the wellbore from an offshore drilling unit (ODU) and rotating a drill bit disposed on a bottom of the tubular string,
wherein:
the drilling fluid exits the drill bit and carries cuttings from the drill bit, and
the drilling fluid and cuttings (returns) flow to a floor of the sea via an annulus defined by an outer surface of the tubular string and an inner surface of the wellbore, and
while drilling the wellbore:
mixing lifting fluid with the returns at a flow rate proportionate to a flow rate of the drilling fluid, thereby forming a return mixture,
wherein:
the lifting fluid has a density substantially less than a density of the drilling fluid,
the return mixture has a density substantially less than the drilling fluid density,
the returns flow from the seafloor, through a subsea wellhead, and into a pressure control assembly (PCA) connected to the subsea wellhead,
a marine riser is connected to the PCA and connected to the ODU by an upper marine riser package (UMRP),
the lifting fluid is mixed with the returns by injection into the UMRP and down an annulus formed between the tubular string and the marine riser, and
the return mixture flows to the ODU via an auxiliary line extending along an outer surface of the marine riser;
measuring a flow rate of the returns or the return mixture; and
comparing the measured flow rate to the drilling fluid flow rate to ensure control of a formation being drilled.

* * * * *